

EPRI

Electric Power
Research Institute

Keywords:

EPRI TR-102134-R5

Non-proprietary version

FINAL REPORT
March 2000

PWR SECONDARY WATER CHEMISTRY GUIDELINES - REV. 5

Prepared by
PWR Secondary Water Chemistry Guidelines Revision Committee

ABOUT EPRI

Electricity is increasingly recognized as a key to societal progress throughout the world, driving economic prosperity and improving the quality of life. The Electric Power Research Institute delivers the science and technology to make the generation, delivery, and use of electricity affordable, efficient, and environmentally sound.

Created by the nation's electric utilities in 1973, EPRI is one of America's oldest and largest research consortia, with some 700 members and an annual budget of about \$500 million. Linked to a global network of technical specialists, EPRI scientists and engineers develop innovative solutions to the world's toughest energy problems while expanding opportunities for a dynamic industry.

EPRI. *Powering Progress*



Printed on recycled paper (50% recycled fiber, including 10% postconsumer waste) in the United States of America.

PWR SECONDARY WATER CHEMISTRY GUIDELINES - REV. 5

TR-102134, Revision 5 - Final Report

Prepared by:

PWR Secondary Water Chemistry Guidelines Revision Committee

ABB-COMBUSTION ENGINEERING
S. Barshay

AmerenUE
G. Schultz

AMERGEN
L. Lucas & R. Walton

AMERICAN ELECTRIC POWER
T. Andert

ARIZONA PUBLIC SERVICE
G. Bucci

BABCOCK & WILCOX-McDERMOTT
P. Doherty, J. Jevic & P. King

BALTIMORE GAS AND ELECTRIC
J. Davis

CAROLINA POWER & LIGHT
C. Bach & J. Nuckles

COMMONWEALTH EDISON
R. Claes & D. Morey

CONSOLIDATED EDISON
R. Burns

CONSUMERS POWER
A. Coddington & J. McElrath

DUKE POWER
R. Eaker, G. Ward & L. Wilson

DUQUESNE LIGHT
V. Linnenbom

ELECTRICITE DE FRANCE
F. Nordmann

ENTERGY OPERATIONS
B. Burke & L. McCollum

FIRST ENERGY
S. Slosnerick

FLORIDA POWER CORPORATION
R. Thompson

FRAMATOME TECHNOLOGIES
M. Bell

HOUSTON LIGHTING AND POWER
S. Daniel

INPO
R. Gossman & T. Parton

LABORELEC
L. Duvivier & C. Goffin

NEW YORK POWER AUTHORITY
M. Kerns

NORTHEAST UTILITIES / NAESCO
G. D'Auria, V. Jones & R. Litman

NORTHERN STATES POWER
S. Lappegaard

NUCLEAR ELECTRIC
A. Bates

NWT
S. Sawochka

OMAHA PUBLIC POWER DISTRICT
B. Schmidt

ONTARIO POWER GENERATION
M. Brett

PACIFIC GAS AND ELECTRIC
F. Guerra

PUBLIC SERVICE ELECTRIC & GAS
S. Harvey

ROCHESTER GAS & ELECTRIC
B. Dahl

SOUTHERN CALIFORNIA EDISON
O. Flores

SOUTHERN NUCLEAR OPERATING
F. Hundley

TU ELECTRIC
B. Fellers

TVA
E. Chandrasekaran & M. King

VATTENFALL, SWEDEN
P.-O. Andersson

VIRGINIA POWER
E. Frese & L. Miller

WESTINGHOUSE
J. Barkich & E. Morgan

WISCONSIN ELECTRIC POWER
G. Corell

WISCONSIN PUBLIC SERVICE
M. Bernsdorf

WOLF CREEK NUCLEAR OPERATING
C. Palmer & T. Jensen

ELECTRIC POWER RESEARCH INSTITUTE
J. Bates & P. Berge, Consultants
P. Frattini, A. McIlree, J. Soriano & N. Torigoe
P. Millett, Chairman

DOMINION ENGINEERING
J. Gorman - Technical Secretary & Consultant

DISCLAIMER OF WARRANTIES AND LIMITATION OF LIABILITIES

THIS PACKAGE WAS PREPARED BY THE ORGANIZATION(S) NAMED BELOW AS AN ACCOUNT OF WORK SPONSORED OR COSPONSORED BY THE ELECTRIC POWER RESEARCH INSTITUTE, INC. (EPRI). NEITHER EPRI, ANY MEMBER OF EPRI, ANY COSPONSOR, THE ORGANIZATION(S) NAMED BELOW, NOR ANY PERSON ACTING ON BEHALF OF ANY OF THEM:

(A) MAKES ANY WARRANTY OR REPRESENTATION WHATSOEVER, EXPRESS OR IMPLIED, (I) WITH RESPECT TO THE USE OF ANY INFORMATION, APPARATUS, METHOD, PROCESS, OR SIMILAR ITEM DISCLOSED IN THIS PACKAGE, INCLUDING MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE, OR (II) THAT SUCH USE DOES NOT INFRINGE ON OR INTERFERE WITH PRIVATELY OWNED RIGHTS, INCLUDING ANY PARTY'S INTELLECTUAL PROPERTY, OR (III) THAT THIS PACKAGE IS SUITABLE TO ANY PARTICULAR USER'S CIRCUMSTANCE; OR

(B) ASSUMES RESPONSIBILITY FOR ANY DAMAGES OR OTHER LIABILITY WHATSOEVER (INCLUDING ANY CONSEQUENTIAL DAMAGES, EVEN IF EPRI OR ANY EPRI REPRESENTATIVE HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES) RESULTING FROM YOUR SELECTION OR USE OF THIS PACKAGE OR ANY INFORMATION, APPARATUS, METHOD, PROCESS, OR SIMILAR ITEM DISCLOSED IN THIS PACKAGE.

ORGANIZATION(S) THAT PREPARED THIS PACKAGE

PWR SECONDARY WATER CHEMISTRY GUIDELINES REVISION COMMITTEE

ORDERING INFORMATION

Requests for copies of this report should be directed to the EPRI Distribution Center, 207 Coggins Drive, P.O. Box 23205, Pleasant Hill, CA 94523, (925) 934-4212.

Electric Power Research Institute and EPRI are registered service marks of the Electric Power Research Institute, Inc. EPRI. POWERING PROGRESS is a service mark of the Electric Power Research Institute, Inc.

Copyright © 2000 Electric Power Research Institute, Inc. All rights reserved.

EPRI FORWARD

Industry water chemistry guidelines are updated periodically as new information becomes available. Previous versions of these guidelines have identified a detailed water chemistry program that was deemed to be consistent with the then current understanding of research and field information. Each version, however, has recognized the impact of these *Guidelines* on plant operation and has noted that utilities should optimize their program based on a plant-specific evaluation prior to implementation. To assist in such plant-specific evaluations, Revision 4, issued in November 1996, provided an increased depth of detail regarding the corrosion mechanisms affecting steam generators and the balance of plant, and provided additional guidance on how to integrate these and other concerns into the plant-specific optimization process. Revision 5 retains the revised format of Revision 4, and adds to the detailed information contained in Revision 4. The sections of Revision 5 cover the following:

- Section 1 identifies Management Responsibilities. It also describes which portions of the *Guidelines* are mandatory under NEI 97-06, Steam Generator Program Guidelines.
- Section 2 presents a compilation of corrosion data for steam generator tubing and, to a lesser extent, balance-of-plant materials. It is not intended to relate operational bulk water chemistry to the corrosion phenomena, which is covered in Section 3. The corrosion data presented in Section 2 serve as the technical bases for each of the specific parameters and programs detailed in the balance of the document.
- Section 3 discusses the role of the concentration processes in the various locations of the steam generator and the chemistry "tools" available for modifying the resulting chemistry within these concentrating regions. It briefly identifies the supporting aspects of and the considerations for adopting these chemistry regimes. It refers the reader to more detailed documents for application of the chemistry strategies. It has been revised to provide a detailed discussion of the integrated exposure concept.
- Section 4 presents a detailed methodology for performing the plant-specific optimization that can be used to develop a modified chemistry program that satisfies site-specific concerns. Section 4 also presents example startup and operating chemistry parameters and limits that can be used as a starting point for site-specific evaluations.
- Sections 5 and 6 present water chemistry programs for RSGs and OTSGs, respectively. These are the sections most frequently referred to by chemistry personnel. The tables contained within these sections provide boundaries of the envelope within which plant-specific optimization should occur.

-
- Section 7 provides information on data collection, evaluation, and management. This section covers use of **EPRI chemWORKS™** modules for evaluating plant data and predicting high-temperature chemistry environments throughout the cycle.
 - Appendix A provides detailed guidance with regard to use of the integrated exposure concept.

These *Guidelines* were produced by the Committee with support from an industry Technical Review Team and the technical committees of the Steam Generator Management Project. Key technical changes in this revision include:

- Guidance was added in Section 1 and in Sections 5 and 6 to clearly indicate that the only portions of the *Guidelines* that are mandatory under NEI 97-06 are 1) the control parameters in Sections 5 and 6, and 2) having a Strategic Water Chemistry Plan. Wording changes were made throughout the *Guidelines* to make clear the non-mandatory nature of the remaining guidance.
- The *Guidelines* have been revised to more clearly indicate that the intent is that all control parameters listed in Sections 5 and 6 be measured using equipment and techniques that provide a reliable or "representative" indication of the measured parameter. The main reason for this change was a growing realization that current equipment and techniques used for measurement of feedwater oxygen are, at many plants, not representative, i.e., do not provide accurate estimates of the actual feedwater oxygen content. Section 7 was revised to provide guidance on how to verify that the feedwater oxygen measurement is representative.
- Sections 5 and 6 were revised to allow condensate dissolved oxygen to be treated as a diagnostic parameter, rather than a control parameter, if the feedwater oxygen measurement has been shown to be representative and the plant does not have copper alloy feedwater heater tubing. An Action Level 2 for feedwater oxygen was also added to both Sections 5 and 6.
- The *Guidelines*, including Sections 5 and 6, were revised to indicate that reducing oxygen to as low as possible may not be desirable, and that maintaining a minimum oxygen level of 1 or 2 ppb in the condensate may help to reduce iron transport.
- Section 6, which covers water chemistry guidelines for OTSGs, was substantially revised to reduce Action Levels for impurities such as sodium, chloride and sulfate and to make it more consistent with the format of Chapter 5, which covers water chemistry guidelines for RSGs.
- All of the sections were reviewed and revised to reflect experience gained and information learned since issuance of Revision 4.
- Section 2 was revised to briefly discuss startup oxidant concerns and to reference the Sourcebook on Limiting Exposure to Startup Oxidants.
- Section 3 was revised to provide a detailed discussion of the integrated exposure concept. Integrated exposure was added as a diagnostic parameter to Sections 5 and 6, which cover water

chemistry guidelines for recirculating steam generators and once-through steam generators, respectively.

- Limits on pH during layup in Sections 5 and 6 were revised from ≥ 9.8 to ≥ 9.5 . This change was based on a review of technical data which showed that there is no strong technical reason to keep $\text{pH} \geq 9.8$, and the fact that a pH limit of ≥ 9.5 is more compatible with use of carbohydrazide.
- Section 7 was substantially revised to provide more details with regard to optimization considering economic factors, effectiveness of the measured parameters, and the key analyses required for assessing chemistry programs.

This revision of the *Guidelines* continues the approach of helping utilities maintain a proactive chemistry program to limit or control steam generator degradation with increased consideration of corporate resources and plant-specific design/operating concerns.

Peter J. Millett
Chairman

ACKNOWLEDGMENTS

Preparation of these guidelines required significant involvement of industry personnel to provide technical review beyond the role of the authoring committee listed on the title page. The personnel in this group of specialists, called the Technical Review Team, are listed below with their organizations for acknowledgment:

William Allmon	Framatome Technologies
Frank Bacon	South Carolina Electric & Gas
Johnny Barker	Tennessee Valley Authority
Richard Barley	AmerGen
Philip Battaglia	Westinghouse Electric
Brent Cederquist	Arizona Public Service
Charles Clinton	South Texas Project
Lewis Crone	Northeast Utilities
Arthur Davis	Virginia Power
Greg Decker	American Electric Power
Robert Dolan	Public Service Electric & Gas
Steve Douglas	Southern Company
Richard Edwards	First Energy
Bruce Fender	Framatome Technologies
Sue Filiatreault	Northeast Utilities
Jeff Gardner	Pacific Gas & Electric
Gail Gary	AmerenUE
Peter Harvey	North Atlantic Energy Service
John Hirsch	Southern California Edison
Robert Hitch	Carolina Power and Light
Mike Holmes	Commonwealth Edison
Lance Hopson	Pacific Gas & Electric
Lee Klett	First Energy
Larry Lamanna	Framatome Technology
Tony Livingston	Southern Company
Jerry Lynch	Carolina Power & Light
John Petro	Commonwealth Edison
William Quarles	Virginia Power
Randall Richards	Wisconsin Electric Power
Robert Richie	Tennessee Valley Authority

Wendy Schneider	Rochester Gas & Electric
Bruce Shubert	Omaha Public Power District
Edward Silva	ABB-Combustion Engineering
David Starke	Commonwealth Edison
Charles Stauffer	Babcock & Wilcox- McDermott
Jim Stevens	TXU
Diana Vincent	British Energy
Dean Weyerberg	Wisconsin Electric Power
Scott Wilson	Northern States Power
Ian Woolsey	British Energy

1

INTRODUCTION AND MANAGEMENT RESPONSIBILITIES

1.1 Introduction And Objectives

Water chemistry programs have been established for operating pressurized water reactors (PWRs) to minimize corrosion concerns. It is recognized that there is no single water chemistry program that provides acceptable corrosion risks and satisfies corporate business objectives. The objective of this document is to provide guidance on determining and implementing a set of plant-specific water chemistry requirements for the secondary cycle of PWRs. Accordingly, this document presents the corrosion data that provides the technical bases for water chemistry control (Section 2), the various water chemistry control strategies that are available (Section 3), a recommended methodology for plant-specific optimization (Section 4), generic water chemistry guidelines for RSGs and OTSGs (Sections 5 and 6, respectively) and suggested data collection, evaluation, and management techniques (Section 7).

In addition, the US nuclear power industry established a framework for increasing the reliability of steam generators by adopting NEI 97-06, *Steam Generator Program Guidelines*. This initiative references EPRI's Water Chemistry Guidelines, including this document, as the basis for an industry consensus approach to chemistry programs. Specifically, the initiative requires that US utilities meet the intent of the *EPRI PWR Secondary Water Chemistry Guidelines*. The focus of the NEI initiative is steam generator integrity. These Guidelines are a support document under NEI 97-06. These *Guidelines* include control parameters and monitoring requirements which must be incorporated into a plant's water chemistry program in order to meet the intent of these guidelines. Section 5 for RSGs and Section 6 for OTSGs address the specific requirements of the secondary water chemistry program relative to the NEI initiative. These sections provide utilities with specific details on the "directive portions" of these *Guidelines* that must be considered to meet the intent of the NEI initiative. Utilities must document exceptions which are less restrictive or less conservative than the control parameters of the *Guidelines*, as found in Sections 5 and 6. Utilities must develop a Strategic Secondary Water Chemistry Plan in response to Section 4 to these guidelines. This plan is intended to be a living document which is approved by utility management. Development of the Strategic Secondary Water Chemistry Plan is necessary to meet NEI 97-06.

1.2 Water Chemistry Management Philosophy

Nuclear station management is charged with generating safe, reliable, and low-cost electric power. Management is periodically faced with a choice of either keeping a unit available to produce power to meet short-term system demands or maintaining good control of chemistry to help assure the long-term integrity of the steam generators, balance-of-plant (BOP), and turbines. To effectively deal with these concerns, it is important that all levels of utility management understand that a successful chemistry program must ensure compliance with regulatory commitments and with established industry guidelines for system/materials integrity, while meeting the economic demands of power generation. Management must understand that operation with off-normal chemistry may result in loss of availability of that unit and that this long-term loss of availability can be minimized by limiting the magnitude and duration of off-normal chemistry. Utility management must support the chemistry guidelines both in principle and in detail at all levels to ensure their effectiveness. The goal should be to extend the operating life of the steam generators, BOP components, and turbines, while providing an acceptable level of unit availability.

The information presented in this section is based on observations that operating and maintenance philosophies with regard to chemistry can significantly affect major component life span. The philosophy and policies discussed reflect the desire to operate in a proactive rather than a reactive mode. The costs associated with maintaining secondary water chemistry within these industry recommendations are likely to be less than those associated with the repair or replacement of steam generators or large turbine rotors and the outages associated with those efforts.

While it is recognized that variety among individual utility organizations exists, there are basic goals and functions common to all. This section addresses key management considerations but makes no attempt to specify how they should be integrated into a specific organizational structure. Additional organizational and administrative guidelines are presented in the *INPO Guidelines for Chemistry at Nuclear Power Stations, Rev. 2* (INPO 88-021, Rev. 2). Utility personnel are encouraged to combine the recommendations in this section with the INPO recommendations when developing/revising their site-specific programs.

This version of the *Guidelines* addresses research results and operational experiences that have developed since publication of Revision 4. Incorporated by reference are several EPRI application guidelines that are used to help implement some of the chemistry control strategies discussed in the sections.

1.3 Generic Management Considerations

This section lists and discusses the considerations which are common to most utilities, including the elements of organizations which are needed to carry out the water chemistry program effectively. Actions are identified without specifying responsibility for completing them. Utility-specific implementation policies and procedures should assign the responsibilities to

specific positions within the organization. One major element of these *Guidelines* is the need for every level of management to understand the importance of the action levels presented in Sections 5 and 6 and their potential impact on, and benefits to, the utility company. In addition, there is a need for management to support a data collection, evaluation and management system similar to the approach discussed in Section 7.

1.3.1 Policies

An important ingredient of a successful management plan for secondary water chemistry control is a set of specific written policies which implement these operating *Guidelines*. Each policy should:

- a. State the need for the policy
- b. State the corporate goal regarding secondary water chemistry and station operation
- c. Highlight corporate management support for the policy/procedure
- d. Assign responsibility for:
 - Preparation and approval of procedures to implement the policy
 - Assessment of the effectiveness of chemistry control in minimizing steam generator degradation
 - Monitoring, analysis, and data evaluation for the chemistry program
 - Surveillance and review functions
 - Corrective actions
- e. Establish the authority to:
 - Carry out procedures
 - Implement corrective actions
 - Resolve disagreements

Procedures implementing these policies normally are separate documents but should, when taken together, contain the level of detail necessary for personnel at all levels to understand and carry out their responsibilities. For plants under construction these procedures should cover both design and operation of the power plant.

The potential for control of operating chemistry is determined during the design phase of a nuclear power plant. As construction of the plant proceeds, the operating procedure options may be limited. Preoperational modifications or equipment additions may be identified as necessary to meet state-of-the-art technology. Post-operational modifications to improve chemistry control should also be considered, when judged to be cost effective.

Utility personnel responsible for plant design in chemistry related areas should:

- a. Understand steam generator design, secondary system materials of construction, and the operational chemistry relationship.
- b. Ensure that the system design is reviewed by experienced plant operating personnel, vendors, and/or consultants, as appropriate.

During the operating phase, the steam generators and turbines are particularly sensitive to water and steam chemistry/purity. Operating procedures should address:

- a. Chemistry control limits and corrective action requirements.
- b. A plant-specific chemistry monitoring/surveillance program to assure that chemistry excursions are quickly identified.
- c. Detailed chemistry procedures containing action levels, specific responses to each action level, and corrective action notification and responsibilities.
- d. Plant approved analytical procedures to ensure accurate laboratory results.
- e. Provisions for data review to assure program implementation.

1.4 Training and Qualification

A program for periodic (continuing) training of all personnel involved with secondary water chemistry control should be established. This program should incorporate the latest information available from EPRI, other utilities, and the steam generator/turbine vendors. Some indoctrination in the basics of the program should be considered for all employees who, by virtue of their job responsibilities, can affect water chemistry.

The training programs should be designed for the level and qualifications of personnel being trained. The following elements should be included:

- a. A clear statement of the corporate policy regarding secondary water chemistry control, including clarification of the impact of this policy upon the various areas of responsibility.
- b. Identification of the impact of poor chemistry control on major component performance, unit availability, and corporate economic performance should be emphasized.
- c. Techniques for recognizing unusual conditions and negative trends should be addressed, particularly for the station chemists and laboratory technicians. Potential corrective actions and their consequences should be thoroughly discussed.
- d. The interaction of system operations and chemistry.

1.5 Summary

It is recognized that a specific program applicable to all plants cannot be defined due to differences in design, experience, management structure, and operating philosophy. However, the goal is to maximize the availability and operating life of major components such as the steam

generator and the turbine. To meet this goal, an effective corporate policy and water chemistry control program are essential and should be based upon the following:

- A recognition of the long-term benefits of, and need for, avoiding or minimizing corrosion degradation of major components.
- Clear and unequivocal management support for operating procedures designed to avoid this degradation.
- Adequate resources of staff, equipment, funds, and organization to implement an effective chemistry control policy.
- An evaluation of the basis for each chemistry parameter, action level and specification, as well as those of similar guidelines.
- Management agreement at all levels, prior to implementing the program, on the actions to be taken in response to off-normal water chemistry and the methods for resolution of conflicts, and unusual conditions not covered by the guidelines.
- Continuing review of plant and industry experience and research and revisions to the program, as appropriate.
- A recognition that alternate water chemistry regimes, if used, should not be a substitute for continued vigilance in adherence to the guidelines.

2

TECHNICAL BASIS FOR WATER CHEMISTRY CONTROL

2.1 Summary

This section of the secondary water chemistry guidelines discusses corrosion issues affecting PWR steam generators and balance of plant components, with the objective of providing bases for selecting secondary water chemistry parameters that minimize problems due to corrosion.

The objective of secondary side water chemistry control is to minimize corrosion damage and performance losses for all secondary system components and to thereby maximize the reliability and economic performance of the secondary system. To achieve this objective, the water chemistry has to be compatible with all parts of the system including steam generators, turbines, condensers, feedwater heaters, moisture separator reheaters (MSRs), and piping. The variety of materials used in the many components in typical secondary systems, and the range of temperatures, pressures, phases, and velocities place constraints on the selection of water chemistries for secondary systems.

Corrosion of steam generator tubes has been the major issue affecting selection of secondary water chemistry parameters. However, corrosion and flow assisted corrosion (FAC) of steam generator internals and other secondary system components are also important concerns.

Corrosion of steam generator tube materials is mainly affected by the following water chemistry related factors, in addition to non-water chemistry factors such as material susceptibility, temperature and stress:

- **pH** - Corrosion of several different types, including intergranular attack/stress corrosion cracking (IGA/SCC) and pitting, are strongly affected by the local pH. High pH (caustic conditions) and low pH (acidic conditions) accelerate the rates of IGA/SCC.
- **Electrochemical Potential (ECP)** - The ECP is a measure of the strength of the oxidizing or reducing conditions present at the metal surface. The occurrence and rate of corrosion processes are strongly affected by the ECP. Secondary side SCC in tube alloys tends to be accelerated by increases in ECP, i.e., by the presence of oxidizing conditions.
- **Specific Species** - Certain specific species accelerate corrosion of tubing alloys. Partly this is a result of the effects of the species on pH and ECP. In addition, some species, such as lead

and reduced sulfur species (e.g., sulfides), appear to interfere with formation of protective oxide films on the tube metal surfaces, and thereby accelerate corrosion, independent of influences on pH or potential.

The above factors have been most thoroughly explored for mill-annealed alloy 600 (600MA). Tests indicate that the other tubing alloys, i.e., stress relieved alloy 600 (600SR), thermally treated alloy 600 (600TT), nuclear grade alloy 800 (800NG) and thermally treated alloy 690 (690TT), exhibit similar tendencies. However, the corrosion rates in these other alloys are generally lower than those exhibited by 600MA, with 690TT generally exhibiting the lowest susceptibility.

Water chemistry selected to protect steam generator tubes appears to be satisfactory for most balance-of-plant (BOP) components such as turbines. The main corrosion concerns in the BOP that affect secondary system water chemistry are flow assisted corrosion (FAC) of carbon steel piping and tubing, and ammonia attack of copper and copper alloy tubes. FAC is mainly influenced by the at-temperature pH and oxygen content around the secondary system. Ammonia attack of copper alloys is mainly influenced by the concentrations of ammonia and oxygen at the copper alloy locations.

Once-through steam generators (OTSGs) have different thermal hydraulics and tube materials than recirculating steam generators (RSGs). These differences have led to OTSGs having somewhat different tube corrosion experience than RSGs of the same vintage. For the most part, OTSGs have experienced somewhat lower rates of tube degradation. However, significant IGA has been detected in the upper bundle free spans of several units, especially at scratches, and steam generator replacement is planned at several units. The mechanisms involved in the IGA are under investigation, and the relationships between the IGA and water chemistry are not as yet established.

2.2 References

1. R. Boueke, "German Experience in Steam Generator Maintenance and Repair," presented at EPRI Steam Generator Strategic Management Workshop, St. Louis, Mo., May 10-12, 1995.
2. P. L. Daniel and S. L. Harper, Use of Pourbaix Diagrams to Infer Local Pitting Conditions, EPRI NP-4831, October 1986.
3. A. Kishida, et al., "Preliminary pH Measurements in High Temperature Simulated PWR Steam Generator Crevice Environments at an On-Site Model Boiler Facility," presented at Symposium on Chemistry in High Temperature Aqueous Solutions, Provo, Utah, August 25-27, 1987.

4. D. Cubicciotti, "Potential - pH Diagrams for Alloy - Water Systems Under LWR Conditions," J. of Nuc. Mat., Vol. 201, pp. 176-183, 1993.
5. R. Staehle, Ed., Control of Corrosion on the Secondary Side of Steam Generators, NACE, 1996.
6. Chapter 10, "Tube Pitting," Steam Generator Reference Book, EPRI, 1985.
7. Chapter 13, "Intergranular Corrosion of Alloy 600 From Caustic Compounds," Steam Generator Reference Book, Revision 1, EPRI, 1994.
8. J. Lumsden, Film analysis of Alloy 600, EPRI TR-112776, May 1999.
9. B. Stellwag, et al., "Influence of SG Water Treatment, Temperature, Cl^- , and O_2 Content on the Pitting Performance of Alloy 800," Proceedings of the International Symposium on Environmental Degradation of Materials in Nuclear Power Systems - Water Reactors, Myrtle Beach, August 22-25, 1983, p947-962, NACE, 1984.
10. K. S. Jeon, et al., "Pitting Corrosion Resistance of Alloy 600 Tubing Material in Nuclear Power Plants," Proceedings of the Fourth International Symposium on Environmental Degradation of Materials in Nuclear Power Systems - Water Reactors, Jekyll Island, August 6-10, 1989, pp. 12-11, 12-22, NACE, 1990.
11. Chapters 13 and 24, Steam Generator Reference Book, Revision 1, EPRI, 1994.
12. A. K. Agrawal and J. P. N. Paine, "Lead Cracking of Alloy 600 - A Review," Proceedings of the Fourth International Symposium on Environmental Degradation of Materials in Nuclear Power Systems - Water Reactors, pp. 7-1 - 7-17, NACE 1990.
13. A. Rocher, et al., "Investigation into Lead Limitation in Steam Generators," Proceedings of the International Symposium - Fontevraud III, Contribution of Materials Investigation to the Resolution of Problems Encountered in Pressurized Water Reactors, p. 537, SFEN, September 12 - 16, 1994.
14. H. Takamatsu, "Study of Pb Induced Attack," in Japanese SG Related R&D Program, presented at EPRI TAG meeting, June 1994.
15. J. A. Gorman and M. J. Partridge, Proceedings: 1987 EPRI Workshop on Mechanisms of Primary Water Intergranular Stress Corrosion Cracking, Alexandria, VA, April 29 - May 1, 1987, p. 6-2, EPRI NP-5987SP, September 1988.
16. J. P. Berge, "Evaluation of Residual Tensile Stresses by Accelerated Stress Corrosion Cracking Tests," Workshop Proceedings: U-Bend Tube Cracking in Steam Generators, EPRI WS-80136, June 1981.

17. S. Harper, et al., "The Role of Sulfur in the Corrosion of NSG," Proceedings of the Third International Symposium on Environmental Degradation of Materials in Nuclear Power Systems - Water Reactors, pp. 457-463, TMS, 1988.
18. T. Sakai, et al., "Corrosion of Alloy 600 in Reduced-Sulfur Containing Solutions at High Temperatures," Zairyo-to-Kankyo, Vol. 40, pp. 736-741, 1991.
19. P. Combrade, et al., "Effect of Sulfur on the Protective Layers of Alloys 600 and 690 in Low and High Temperature Environments," Proceedings of the Fourth International Symposium on Environmental Degradation of Materials in Nuclear Power Systems - Water Reactors, pp. 5-79 - 5-95, NACE 1990.
20. W. H. Cullen and M. J. Partridge, Susceptibility of Alloys 600 and 690 to Acidified Sulfate and Chloride Environments, EPRI TR-104045, June 1994.
21. Chapters 10 and 24, Steam Generator Reference Book, Revision 1, EPRI, 1994.
22. B. Stellwag, et al., "Corrosion Resistance of SG Tubing Materials Alloy 800 and Alloy 690 - A Comparative Study," Proceedings of the Third International Symposium on Environmental Degradation of Materials in Nuclear Power Systems - Water Reactors, pp. 301-310, TMS, 1988.
23. L. G. Ljungberg, et al., "Effects of Some Seldom Noticed Water Impurities on Stress Corrosion Cracking of BWR Construction Materials," Corrosion, Vol. 45, No. 3, pp. 215-222, March 1989.
24. P. L. Andresen, "Effects of Specific Anionic Impurities on Environmental Cracking of Austenitic Materials in 288°C Water," Proceedings of the Fifth International Symposium on Environmental Degradation of Materials in Nuclear Power Systems - Water Reactors, pp. 209-218, ANS, 1992.
25. B. W. Bussert and F. D. Miller, "Round Robin Stress Corrosion Testing of Alloy 600 Split Tube U-Bends," Proceedings: 1991 EPRI Workshop on Secondary-Side Intergranular Corrosion Mechanisms, EPRI TR-101103, August 1992.
26. H. Nagano, "Alkaline Intergranular Corrosion and Stress Corrosion Cracking of Alloy 600," Control of Corrosion on the Secondary Side of Steam Generators, pp. 259-271, NACE, 1996.
27. B. Sala, et al., "The Use of Tube Examinations and Laboratory Simulations to Improve the Knowledge of Local Environments and Surface Reactions in TSPs," Control of Corrosion on the Secondary Side of Steam Generators, pp. 483-497, NACE, 1996.
28. J. Daret, "IGA/IGSCC in Non-Caustic Waters - CEA Experience," CEA, July 1989.

29. Y. Lefevre and J. Daret, Corrosion des Tubes de Générateurs de Vapeur Côté Secondaire, Bilan des Essais en Boucle AJAX Realises dan le Cadre de la Revision No. 2, CEA Report SCECF No. 354, Dec. 1994.
30. J. Daret, "Model Boiler Tests, Phosphate," presented at EPRI Workshop on Steam Generator Secondary Side IGA/SCC, Minneapolis, MN, October 14 - 15, 1993.
31. E. Pierson, et al., "How to Simulate Acid Corrosion of Alloy 600 Steam Generator Tubes," Proceedings of the Seventh International Symposium on Environmental Degradation of Materials in Nuclear Power Systems - Water Reactors, p. 303, NACE, 1995.
32. G. Pinard-Legry and G. Plante, Intergranular Attack of Alloy 600: High Temperature Electrochemical Tests, EPRI NP-3062, May 1983.
33. J. R. Balavage, Effect of Calcium Hydroxide and Carbonates on IGA and SCC of Alloy 600, EPRI NP-3060, May 1983.
34. S. R. Piskor, Boric Acid Application Guidelines for Intergranular Corrosion Inhibition (Rev. 1), EPRI NP-5558, Rev. 1, December 1990.
35. J. B. Lumsden, et al., "Mechanism and Effectiveness of Inhibitors for SCC in a Caustic Environment," Proceedings of the Seventh International Symposium on Environmental Degradation of Materials in Nuclear Power Systems - Water Reactors, pp. 317-325, NACE, 1995.
36. W. A. Byers and R. J. Jacko, "The Influence of Zinc Additions and PWR Water Chemistry on Surface Films that Form on Nickel Base Alloys and Stainless Steels," Proceedings of the Sixth International Symposium on Environmental Degradation of Materials in Nuclear Power Systems - Water Reactors, pp. 837-844, TMS, 1993.
37. A. J. Baum, et al., "Development of Improved PWR Secondary Water Chemistry Guidelines," Proceedings Eighth International Symposium on Environmental Degradation of Materials in Nuclear Power Systems - Water Reactors, p74-79, ANS, 1997.
38. P. J. Prabhu, et al., "ODSCC Algorithm Shows Correlation with Degradation," Third International Steam Generator & Heat Exchanger Conference," Toronto, ON, June 21-24, 1998, CNS.
39. P. J. Prabhu, "A Review of the Effects of Silica on Stress Corrosion Cracking of Steam Generator Tubes," presented at Ninth International Symposium on Environmental Degradation of Materials in Nuclear Power Systems - Water Reactors, Newport Beach, CA, October 1-5, 1999, TMS.
40. R. W. Staehle, "Occurrences of Modes and Submodes of IGC and SCC," Control of Corrosion on the Secondary Side of Steam Generators, pp. 135-208, NACE, 1996.

41. H. Takamatsu, et al., "Monitoring on Corrosion Behavior of Steam Generator Tubings," 1988 JAIF International Conference on Water Chemistry in Nuclear Plants, pp. 648-653, JAIF, 1988.
42. H. Takamatsu, et al., "IGA/SCC Crack Propagation Rate Measurements on Alloy 600 Steam Generator Tubing Using a Side Stream Model Boiler," Proceedings of the Sixth International Symposium on Environmental Degradation of Materials in Nuclear Power Systems - Water Reactors, pp. 81-88, TMS, 1993.
43. B. P. Miglin and J. M. Sarver, Investigation of Lead as a Cause of Stress Corrosion Cracking at Support Plate Intersections, EPRI NP-7367-S, June 1991.
44. T. Sakai, et al., "Corrosion of Alloy 600 in Reduced-Sulfur Containing Solutions at High Temperatures," Zairyo to Kankyo, Vol. 40, no. 11, pp. 736-741, November 15, 1991.
45. O. Cayla, et al., "Influence of Sulfide and Sulfate Ions on the Corrosion of Alloy 600 in Deaerated Solutions at High Temperature," 1987 EPRI Workshop on Secondary-Side Intergranular Corrosion Mechanisms: Proceedings, EPRI NP-5971, September 1988.
46. Tsujikawa and S. Yashima, "Results of Steam Generator Reliability Test," Proceedings of a Conference on Steam Generators and Heat Exchangers, Toronto, June 1994, Vol. 2, p. 6.73, CNS, 1994.
47. T. Sakai, et al., "Lead-Induced Stress Corrosion Cracking of Alloy 600 and 690 in High Temperature Water," Proceedings of the Fifth International Symposium on Environmental Degradation of Materials in Nuclear Power Systems - Water Reactors, pp. 764-772, ANS, 1992.
48. K. K. Chung, et al., "Lead Induced Stress Corrosion Cracking of Alloy 690 in High Temperature Water," Proceedings of the Seventh International Symposium on Environmental Degradation of Materials in Nuclear Power Systems - Water Reactors, pp. 233-246, NACE, 1995.
49. E. Pierson, et al., "Stress Corrosion Cracking of Alloys 690, 800 and 600 in Acid Environments Containing Copper Oxides," Paper No. 119, Corrosion 96, NACE, 1996.
50. J. F. Newman, Stress Corrosion of Alloys 600 and 690 in Acidic Sulfate Solutions at Elevated Temperatures, EPRI NP-3043, October 1983.
51. M. A. Kreider, et al., "Corrosion Mode Diagrams for Alloy 690 TT and Alloy 800," Proceedings of the International Symposium Fontevraud III, Contribution of Materials Investigation to the Resolution of Problems Encountered in Pressurized Water Reactors, SFEN 12-16 Sept. 1994.

52. D. Gómez Briceño, et al., "Susceptibility of Steam Generator Tubes in Secondary Conditions," CNRA/CSNI Workshop on Steam Generator Tube Integrity in Nuclear Power Plants, October 20 - November 2, 1995, Argonne National Laboratory.
53. R. L. Tapping, et al., "The Susceptibility of CANDU Steam Generator Tubing Alloys to IGA/IGSCC in Acid Sulfate Environments," AECL Report COG-93-295, December 1993.
54. P. Millett, Proj. Mgr., PWR Molar Ratio Control Application Guidelines, Volume 1, Summary, EPRI TR-104811, Vol. 1, January 1995.
55. S. Pagan, "Bruce A Unit 2 SGs 1 - 4, Lead Crack Growth Rate Data," April 25, 1996 (Ontario Hydro calculation).
56. Draft update to Chapter 24, "Material Selection and Alternative Designs for Steam Generators," Steam Generator Reference Book, Revision 1, submitted for publication by EPRI.
57. R. L. Tapping, et al., "Scoping Tests to Determine the Primary Water Stress Corrosion Cracking of CANDU Steam Generator Tubing," Proceedings of a Conference on Steam Generators and Heat Exchangers, CNS, 1990.
58. S. R. Piskor, Boric Acid Application Guidelines for Intergranular Corrosion Inhibition, Revision 1, Appendix C, EPRI NP-5558-SL, Dec. 1990.
59. K. R. Craig, "Summary of Combustion Engineering, Inc. Pot/Model Boiler Tests," Proceedings: Workshop on the Role of Sulfur Species on the Secondary-Side Degradation of Alloy 600 and Related Alloys, EPRI NP-6710, March 1990.
60. M. Partridge and J. Daret, Inhibition of IGA/SCC on Alloy 600 Surfaces Exposed to PWR Secondary Water, EPRI TR-106212-V3, Nov. 1998.
61. J. Daret, "IGA/SCC in Non-Caustic Waters," presented at 1989 EPRI contractors meeting in Pittsburgh.
62. Y. Lefevre and J. Daret, Corrosion des Tubes de Générateurs de Vapeur Côté Secondaire, Bilan des Essais en Boucle AJAX Realises dan le Cadre de la Revision No. 2, CEA Report SCECF No. 354, Dec. 1994.
63. Y. Lefevre, Corrosion des Tubes de Générateurs de Vapeur Côté Secondaire, Bilan des Essais en Boucle AJAX Realises dan le Cadre de la Revision No. 3, CEA Report SCECF No. 381, Dec. 1995.
64. J. Daret, et al., ""Evidence for the Reduction of Sulfates Under Representative SG Secondary Side Conditions, and for the Role of Reduced Sulfates on Alloy 600 Tubing Degradation," presented at the Ninth International Symposium on Environmental Degradation in Nuclear Power Systems - Water Reactors, Newport Beach, California, August 1-5, 1999.

65. W. Allmon, "Conditions for the Reduction of Sulfates," Workshop on Sulfur Species on the Degradation of Alloy 600 and Similar Alloys, EPRI NP-6710, March 1990.
66. D. A. Palmer, Volatility of Aqueous Sodium Hydroxide, Bisulfate and Sulfate, EPRI TR-105801, Fe. 1999.
67. A. P. L. Turner, J. A. Gorman, et al., Statistical Analysis of Steam Generator Tube Degradation: Additional Topics, EPRI TR-103566, July 1994.
68. B. Prioux, et al., "Secondary Side Cracking at Saint-Laurent Unit B1: Investigations, Operating Chemistry and Corrosion Tests," Contribution of Materials Investigation to the Resolution of Problems Encountered in Pressurized Water Reactors. Proceedings of the International Symposium - Fontevraud III - September 12-16, 1994, pp. 383-393, SFEN, 1994.
69. J. V. Monter, Specially Prepared Alloy 600 Tubing, EPRI NP-5072, Feb. 1987.
70. Personal discussions with several EdF and Framatome researchers.
71. F. Vaillant, et al., "Effects of Microstructure and Mechanical Properties of Alloys 600 and 690 on Secondary Side SCC," Control of Corrosion on the Secondary Side of Steam Generators, p321-335, NACE, 1996.
72. Chapter 24, Steam Generator Reference Book, Revision 1, EPRI, 1994.
73. P. Doherty, et. al. "On the Influence of Manufacturing Practices on the SCC Behaviour of Alloy 690 Steam Generator Tubing," Control of Corrosion on the Secondary Side of Steam Generators, p401-417, NACE, 1996.
74. P. E. Doherty, et al., "Mechanical/Electrochemical Performance of Alloy 690 Steam Generator Tubing," Proceedings Eighth International Symposium on Environmental Degradation of Materials in Nuclear Power Systems - Water Reactors, p157-166, ANS, 1997.
75. J. Gorman, Guidelines for Procurement of Alloy 690 Steam Generator Tubing, EPRI NP-6743-L, Volume 2, Revision 1, p3-9, February 1999.
76. N. Nagano, "Effects of Environmental and Metallurgical Factors on the IGA/SCC of Alloy 600," Proceedings: 1991 EPRI Workshop on Secondary-Side Intergranular Corrosion Mechanisms, EPRI TR-101103, August 1992.
77. Telephone conversation between D. Macdonald of Penn State and J. Gorman of DEI, August 19, 1996.
78. R. W. Staehle, "Occurrence of Modes and Submodes of SCC," Control of Corrosion on the Secondary Side of Steam Generators, p135-208, NACE, 1996.

79. N. Pessall, "Prediction of Stress Corrosion Cracking in 10% Caustic Soda Solutions at 315°C (600°F)", Corrosion Science, Vol. 20, pp. 225-242, 1980.
80. P. E. C. Bryant and J. E. Lesurf, "Some Observations of Intergranular Corrosion on Iron and Nickel Alloys in High Purity Water," presented at Corrosion 68, NACE.
81. Discussion on page 2-18 of TR-101103 of "Round Robin Stress Corrosion Testing of Alloy 600 Split Tube U-Bends," B. W. Bussert, Proceedings: 1991 EPRI Workshop on Secondary-Side Intergranular Corrosion Mechanisms, EPRI TR-101103, August 1992.
82. Chapter 7, "Primary Water Stress Corrosion Cracking," Steam Generator Reference Book, Revision 1, pp. 7-53 - 7-56, EPRI, 1994.
83. G. Economy and F. Pement, "Temperature Effects on Alloy 600 PWSCC from 310 to 330 °C (590 to 626 °F). Paper No. 493 at Corrosion 89, NACE, 1989.
84. Staehle, et al., Corrosion and Corrosion Cracking of Materials for Water-Cooled Reactors, EPRI, NP-1741, March 1981.
85. J. B. Lumsden, et al., "Hideout in Prototypic Tube/Tube Support Plate Heated Crevices Using Laboratory Feedwater and Ohi-1 Blowdown," presented at JAIF conference, Kashiwazaki, Japan, October 1998.
86. J. A. Gorman, "Correlation of Hot Leg Temperature with Rate of Steam Generator Tube Corrosion," draft report for EPRI, February 1993.
87. B. L. Dow, Jr., Steam Generator Progress Report, Revision 10, EPRI, November 1994.
88. I. Ohsaki, et al., "Study of the Improvement of Steam Generator Tubing and Tube Support Plate Materials," presented at the Second International SG and HE Conference, Canadian Nuclear Society, Toronto, June 1994.
89. R. S. Pathania and P. V. Balakrishnan, Correlation of Tube Support Structure Studies, EPRI NP-4672, July 1986.
90. S. G. Sawochka, et al., Transport of Lead in PWR Secondary Cycles, EPRI NP-7158, April 1991.
91. G. E. Brobst and J. M. Riddle, PWR Molar Ratio Control Application Guidelines, Volume 3: Hideout Return Evaluation Guidelines, EPRI TR-104811-V3, November 1995.
92. Chapter 10, "Tube Pitting," Steam Generator Reference Book, Revision 1, EPRI, 1994.
93. A. Brennenstuhl and F. Gonzalez, "Comparative SIMS Analysis of the Alloy N04400 Batches Used at Pickering NGS," OHRD Report 92-128-K, June 92.

94. A. Brennenstuhl et al., "The Use of Electrochemical Noise to Investigate the Corrosion Resistance of UNS Alloy N04400 Nuclear Heat Exchanger Tubes," paper presented at ASTM Symposium on Electrochemical Noise Measurements for Corrosion Applications, May 1994.
95. P. M. Scott and P. Combrade, "On the Mechanisms of Secondary Side PWR Steam Generator Tube Cracking," 8th International Symposium on Environmental Degradation of Materials in Nuclear Power Systems - Water Reactors, Amelia Island, FL, p65-73, ANS, 1997.
96. Survey and Characterization of Feedwater Venturi Fouling at Nuclear Power Plants, EPRI TR-100514, Vol. I and II, May 1992.
97. Identifying Antifouling Coatings for Venturis, EPRI TR-101256, October 1992.
98. "Ethanolamine Eliminates Feedwater Venturi Fouling," Innovators With EPRI Technology, EPRI, November 1994.
99. T. P. Gillespie, Jr., "Development of the Feedwater Venturi Fouling Coefficient," Transactions of the American Nuclear Society, Vol. 62, pp. 420-421, 1990.
100. J. T. Lovett and B. L. Dow, Steam Generator Performance Degradation, EPRI NP-7524, September 1991.
101. P. Sherburne et al., Ginna Station Steam Generator U-Bend Tube Analysis for Chemical Cleaning Data, EPRI TR-100866, July 1992.
102. G. A. White, et al., "Causes of PWR Steam Generator Thermal Performance Degradation," presented at the sixth EPRI PSE Nuclear Plant Performance Seminar, Sep. 3-4, 1996, Asheville, N. C.
103. R. D. Varrin, Jr., Characterization of PWR Steam Generator Deposits, EPRI TR-106048, February 1996.
104. Nishikawa et al., "Experimental Investigation of Scale Formation at Heat Transfer Surface in PWR Secondary System," Chemistry in Water Reactors: Operating Experience and New Developments, pp. 579-586, SFEN, 1994.
105. C. W. Turner and S. J. Klimas, The Effect of Alternative Amines on the Rate of Boiler Tube Fouling, EPRI TR-108004, September 1997.
106. C. W. Turner, Surface Chemistry Interventions against Tube Fouling, EPRI TR-110083, Dec. 1999.
107. H. E. C. Rummens and C. W. Turner, "Experimental Study of Flow Patterns Near Tube Support Structures," Steam Generator and Heat Exchanger Conference, Toronto 1996, Conference Proceedings, Volume 1, pp4.33 - 4.49, CNS, 1994.

108. J. B. Lumsden et al., "Mechanism and Effectiveness of Inhibitors for SCC in a Caustic Environment," Proceedings of the Seventh International Symposium on Environmental Degradation of Materials in Nuclear Power Systems - Water Reactors, Vol. 1, pp. 317-325, NACE, 1995.
109. M. Koike, et al., "Effect of Boric Acid on IGA/SCC Propagation Rate of Alloy 600 in High Temperature Water," presented at EPRI Workshop on Steam Generator Secondary Side IGA/SCC, October 14 & 15, 1993, Minneapolis, Minnesota.
110. M. J. Partridge et al., Correlation of Secondary-Side IGA/SCC Degradation of Recirculating Steam Generator Tubing With the On-Line Addition of Boric Acid, EPRI TR-101010, August 1992.
111. G. E. von Nieda et al., "Denting in Nuclear Steam Generators - Laboratory Evaluation of Carbon Steel Corrosion Under Heat Transfer Conditions," Materials Performance, pp. 38-45, June 1981.
112. R. G. Varsanik and D. L. Gibbons, Characterization of Single-Tube Model Boiler Dented Intersection Specimens, EPRI NP-3024, May 1983.
113. J. G. Singer, Ed., Combustion, Combustion Engineering, Inc., 1981.
114. Chapter 9, "Tube Wastage and Phosphate Secondary Water Chemistry," Steam Generator Reference Book, Revision 1, EPRI, December 1994.
115. C. Laire et al., "DOEL 4: Secondary Side Corrosion Mechanisms and Effects of Phosphate Injection," Proceedings of the Specialists Meeting on Steam Generator Problems and Replacements, Madrid, Spain, December 13-16, 1993, IAEA, 1994.
116. J. B. Lumsden, B. P. Miglin, and J. P. N. Paine, "Mechanism and Effectiveness of Inhibitors for IGA/SCC," Proceedings of the International Symposium - Fontevraud III, Contribution of Materials Investigation to the Resolution of Problems Encountered in Pressurized Water Reactors, Vol. 2, pp. 505-511, SFEN, September 12-16, 1994.
117. B&W Nuclear Service Company, Sourcebook for Plant Layup and Equipment Preservation (Revision 1), EPRI NP-5106, Revision 1, May 1992.
118. W. F. Cleary, Evaluation and Categorization of Secondary System Layup and Cleanup Practices for PWR Plants, EPRI NP-2656, p. S-5, December 1982.
119. Source Book on Limiting Exposure to Startup Oxidants, EPRI TR-112967, September 1999, and Proceedings: 1999 EPRI Workshop on Startup Oxidant Control, EPRI TR-112815, June 1999.

120. P. Berge and F. Nordmann, "PWR Secondary Water Chemistry and Corrosion," Proceedings of the Third International Symposium on Environmental Degradation of Materials in Nuclear Power Systems - Water Reactors, pp. 22-30, TMS, 1988.
121. W. L. Pearl, et al., "Corrosion Product Release Rate from Alloy 706 in Condenser Applications," Proc. Amer. Power Conf., Vol. 38, pp. 890-899, 1980.
122. Chapter 18, "Corrosion Product Control," Steam Generator Reference Book, EPRI, 1985.
123. Telefax dated 7-18-96 from P. J. Harvey, Seabrook Station, to G. Brobst.
124. F. J. Pocock et al., "Control of Iron Pickup in Cycles Utilizing Carbon Steel Feedwater Heaters," Proc. Amer. Power Conf., Vol. 28, pp. 758-722, 1966.
125. K. Steit and S. Odar, "10 Years of Field Experience With High-AVT Water Chemistry," Chemistry in Water Reactors: Operating Experience and New Developments, pp. 571-578, SFEN, 1994.
126. PWR Secondary Water Chemistry Guidelines Revision Committee, "Appendix E - Alternate Amines for Secondary System pH Control," PWR Secondary Water Chemistry Guidelines- Revision 3, EPRI TR-102134, Rev. 3, May 1993.
127. T. Schwarz and V. Schneider, "Influence of SG Design and Water Chemistry on Sludge Accumulation in Siemens Steam Generators," presented at EPRI Sludge Management Workshop, Norfolk, Virginia, May 10 - 12, 1994.
128. B. Chexal, et al., Flow-Accelerated Corrosion in Power Plants, EPRI TR-106611-R1, 1998.
129. G. Bohnsack, The Solubility of Magnetite in Water and Aqueous Solutions of Acid and Alkali, Vulkan-Verlag, 1987.
130. I. S. Woolsey et al., "The Influence of Oxygen and Hydrazine on the Erosion-Corrosion Behavior and Electrochemical Potentials of Carbon Steel Under Boiler Feedwater Conditions," BNES Conference on Water Chemistry of Nuclear Reactor Systems, 4, BNES, London, 1986.
131. R. Litman, "Condensate Oxygen Control at Seabrook Station," presented at PWR Plant Chemistry Meeting, Huntington Beach, California, September 1-3, 1998; supplemented by Litman-Gorman telecon on 12/20/99.
132. S. Harvey of PSE&G, email to P. Millett of EPRI dated Nov. 21, 1999.
133. F. Anderson, "Analysis of Iron Transport and Oxygen Levels," presented at EPRI Plant Water Chemistry Meeting, Lake Buena Vista, Fl., November 1 - 3, 1995.

134. O. de Bouvier, "Influence of the Hydrazine Content on the Rate of Corrosion-Erosion of Carbon Steels - Report on Tests in the CIROCO Loop," EDF-DER report dated December 8, 1998.
135. O. de Bouvier, "Program on the CIROCO loop - Influence of Hydrazine on FAC in the presence of Oxygen - Program for Chrome," presented at CHUG meeting, Portland, June 17-18, 1999.
136. P. Berge comment related to Section 2.5, page 2-45 of Integrated Draft of Guidelines, documented in Attachment D to minutes of meeting of February 17-18, 2000 meeting of the Secondary Water Chemistry Guidelines Committee.
137. F. F. Lyle, Jr., "Low-Pressure Steam Turbine Disc Cracking - An Update," Journal: Proceedings of the Institution of Mechanical Engineers, Part A, Power and Process Engineering, Vol. 199 (1), pp. 59-67, 1985.
138. N. Sastry Cheruvu and B. B. Seth, "Key Variable Affecting the Susceptibility of Shrunk-On Discs to Stress Corrosion Cracking," Proceedings of the 1993 International Joint Power Generation Conference, PWR-Vol. 21, The Steam Turbine Generator Today: Materials, Flow Path Design, Repair and Refurbishment, pp. 43-56, ASME, 1993.
139. P. C. Cohen, Ed., The ASME Handbook on Water Technology for Thermal Power Systems, p. 1393, ASME, 1989.
140. O. Jonas and N. F. Rieger, Turbine Steam, Chemistry, and Corrosion, EPRI TR-103738, August 1994.
141. G. D. Burns, PWR Advanced Amine Application Guidelines, EPRI TR-102952, December 1994.
142. L. D. Kramer and M. P. Weisel, "Avoiding Corrosion of Steam Turbine Components During Erection and Layup," ASME Paper 78-JPGC-Pwr-5.
143. F. Lyle, Jr., "Stress Corrosion Cracking in Low-Pressure Steam Turbines - and Overview," Paper No. 219, Corrosion 94, NACE, 1994.
144. J. A. Beavers and A. K. Agrawal, "Corrosion in Power Plant Condensers: An Overview," Proceedings of the Third International Symposium on Environmental Degradation of Materials in Nuclear Power Systems - Water Reactors, pp. 39-45, TMS, 1988.
145. B. N. McDonald and L. E. Johnson, "Nuclear Once-Through Steam Generator," presented to the American Nuclear Society, September 1970.
146. L. E. Johnson, Secondary-Side Chemistry Investigations in a 37-Tube Nuclear Once-Through Steam Generator, ARC-4599, B&W Alliance Research Center, February 6, 1970.

147. D. P. Rochester, et al., "Results of Laboratory Examinations of Tubes from Oconee Nuclear Station Once Through Steam Generators," Proceedings of the International Symposium Fontevraud IV, Contribution of Materials Investigation to the Resolution of Problems Encountered in Pressurized Water Reactors, p513-527, SFEN 14-18 Sept. 1998.

3

WATER CHEMISTRY CONTROL STRATEGIES

3.1 Introduction

Section 2 discussed the corrosion mechanisms that can lead to degradation of steam generator tubing, with specific emphasis on the corrosion of alloy 600MA. Section 2 also noted that alloys 600SR, 600TT, 800NG, and 690TT are subject to the same corrosion mechanisms as alloy 600MA, though somewhat more resistant. This section presents a variety of chemistry control strategies that can be used to adjust those parameters that were shown to accelerate corrosion of steam generator tubing materials. Included in this section are:

- ALARA Chemistry Control
- Molar Ratio Control (MRC)
- Low Power Soaks
- Elevated Hydrazine
- pH and ORP Optimization to Minimize Iron Transport
- Elimination of Specific Impurities
- Boric Acid Treatment (BAT)
- Injection of Corrosion Inhibitors
- Steam Generator Chemical Cleaning
- Sludge Lancing

Before discussing these options, this section will first discuss the role of the localized concentration processes. It is believed that the localized concentration factors achieved in flow-occluded regions are responsible for development of localized chemistry environments that are quite different from bulk water chemistry.

3.2 Role of Concentration Processes

Chemistry is controlled outside the steam generator to limit transport of impurities into the steam generator. Most impurities are at or near their minimum detectable concentrations by traditional analytical techniques. When the impurities increase above preset concentrations, actions are taken by station personnel that may include reduced power operation or plant shutdown. These Action Levels and associated concentrations are described in detail in Sections 4, 5 and 6. All of the chemistry parameters controlled during normal operation are based on room-temperature analyses of cooled samples of condensate, feedwater or steam generator blowdown. Despite the

various sample locations to which Action Levels are applied, all species are controlled based on their impact on the various steam generator, BOP and turbine corrosion processes.

It is understood by most that the concentrating effects of the steam generators are necessary to produce localized environments that are aggressive to steam generator tubing materials.

3.3 Control of Steam Generator Deposits

Corrosion products deposited in steam generators may develop flow-occluded crevices where bulk water can concentrate in a thermodynamically-limited fashion. There is also a correlation between the location of pitting and wastage and the sludge deposited on the top of the tubesheet. Hence, the presence of corrosion product deposits are considered a precursor to the development of environments where localized chemistry can be a contributor to corrosion. (Note that tube-to-support contact locations also can be regions where concentrated solutions develop even in the absence of deposits.) An additional concern with deposits is that they can be oxidized during layup, especially under uncontrolled drained conditions, increasing the risks of undesirable oxidizing conditions being present in localized areas during subsequent operation. For this reason, the time that steam generators are in uncontrolled drained conditions should be minimized.

The first line of defense against deposit induced problems is to minimize the ingress and accumulation of deposits by appropriate water chemistry controls, as discussed earlier in this section. However, despite rigorous water chemistry control, undesirable amounts of deposits can accumulate. Techniques to remove such deposits include sludge lancing and chemical cleaning.

3.4 References

1. The ASME Handbook on Water Technology for Thermal Power Systems, Paul Cohen, Editor-in-Chief. The American Society of Mechanical Engineers, New York, New York. 1989. Section 6.3, Allen J. Baum, Editor.
2. P. Cohen, Water Coolant Technology of Power Reactors, American Nuclear Society, New York. 1969.
3. P. V. Balakrishnan, et al, "Hideout of Sea Water Impurities in Steam Generator Tube Deposits: Laboratory and Field Studies," Proceedings of the Seventh International Symposium on Environmental Degradation of Materials in Nuclear Power Systems - Water Reactors, v1, p 375, NACE, 1995.
4. PWR Molar Ratio Control Application Guidelines, Volume 1: Summary, Electric Power Research Institute, Palo Alto, Calif.: Research Project S520 Final Report. November 1995. TR-104811-V1.
5. Hideout and Return of Complex Mixtures in Crevices, EPRI NP-7494, September 1991.

6. C. Fauchon and P. J. Millett, "Application of Modeling Local Chemistry in a PWR Steam Generator," Secondary Water Chemistry Guidelines Revision Meeting, Washington D.C., 1999.
7. Development of a Steam Generator Heated Crevice Monitor, EPRI TR-108755, Nov. 1998.
8. P. V. Balakrishnan, "Hideout and Return of Complex Mixtures in Crevices," EPRI Report NP-7494, 1991.
9. F. Gonzalez and P. Spekkens, "Concentration Processes under Tubesheet Sludge Piles in Nuclear Steam Generators," Nuclear Journal of Canada, vol 1:2, 129-240.
10. A. J. Baum, "Restricted Geometries and Deposits," The ASME Handbook on Water Technology For Thermal Power Systems, P. Cohen, editor, ASME, Chapter 6.
11. J. G. Cleary, G. E. Von Neida, and W. T. Lindsay, "Diffusion and Hideout in Crevices," EPRI Report NP-2979, 1983.
12. P. J. Millett and J. M. Fenton, "Transport Processes in PWR Support Structure Crevices," Proceedings of Environmental Degradation of Materials in Nuclear Power Systems-Water Reactors, Jekyll Island, 1989.
13. J. Stevens, "Chemistry Strategies and Results at Comanche Peak," Proceedings: 1999 EPRI Workshop on Startup Oxidant Control, EPRI TR-112815, June 1999.
14. Evaluation of Steam Generator Chemical Hideout at the Prairie Island PWR, Electric Power Research Institute, Palo Alto, Calif: February 1988. NP-55592.
15. Prairie Island-2 Steam Generator Hideout, Electric Power Research Institute, Palo Alto, Calif: April 1991. NP-7236.
16. J.-M. Fiquet, A. Stutzmann, M. Blain, "Comparison of Hideout Tests on Different Steam Generators." Presented at the EPRI PWR Plant Chemistry Meeting, Lake Buena Vista, FL. November 1, 1995.
17. H. Takamatsu, "Evaluation of SG Crevice Environment by Directly Sampled Method Using an On Site Autoclave Facility," Proceedings of the Fifth International Symposium on Environmental Degradation of Materials in Nuclear Power Systems - Water Reactors, p752-756, ANS, 1992.
18. J. Lumsden, et al., "Hideout in Prototypic Tube/Tube Support Plate Heated Crevices Using Laboratory Feedwater and Ohi-1 Blowdown," attached to minutes of May 5-7, 1999 PWR Secondary Chemistry Water Chemistry Guidelines Meeting, issued on June 3, 1999.

19. P. V. Balakrishnan, "Hideout, Hideout Return and Crevice Geometry in Steam Generators," presented at 13th International Conference on Properties of Steam And Water, Toronto, September 12-16, 1999.
20. P. J. Millett and F. Hundley, "Optimization of Secondary Water Chemistry in US PWRs," Nuclear Energy, v36, n4, p251-258, August 1997.
21. A. K. Agrawal and J. P. N. Paine, "Lead Cracking of Alloy 600--A Review," Proceedings of the Fourth International Symposium on Environmental Degradation of Materials in Nuclear Power Systems - Water Reactors, p7-1 to 7-17, NACE, 1990.
22. Boric Acid Application Guidelines for Intergranular Corrosion Inhibition - Revision 1, Electric Power Research Institute, Palo Alto, Calif.: NP-5558-SL
23. Correlation of Secondary-Side IGA/SCC Degradation of Recirculating Steam Generator Tubing with the On-Line Addition of Boric Acid, Electric Power Research Institute, Palo Alto, Calif.: Research Project S407-07 Topical Report. August 1992. TR-101010.
24. Tube degradation analyses performed by DEI for Ameren and SCE, 1998 and 1999.

4

METHODOLOGY FOR PLANT-SPECIFIC OPTIMIZATION

4.1 Introduction

Due to the wide range of conditions and materials of construction in the secondary system, no single optimum water chemistry program can be specified for all PWRs. As such, a site-specific optimized water chemistry program requires development. This program should consider factors such as steam generator and BOP component design and operating history and use of condensate and/or blowdown demineralizers. The overall objective of the optimization is to maximize the total avoided costs from corrosion and other performance related issues while minimizing operating costs. Since a cost/benefit analysis for the secondary system cannot be completed with great certainty, the approach presented here considers the relative risks/benefits of various chemistry programs on a component-by-component basis. It is recognized that tradeoffs exist whereby optimization of the water chemistry program for one component (e.g. steam generators) could negatively impact costs of operating other components (e.g. demineralizers). The relative importance of individual components should be evaluated based on utility and plant-specific considerations. The goal of this section of the guidelines is to provide a basis for establishing an optimized secondary water chemistry program, not to prescribe the program in detail.

The development of a cost/benefit analysis for secondary chemistry is difficult for several reasons. First, the long-term benefits of water chemistry cannot be easily quantified, although the value of minimizing corrosion is well understood. For example, lower steam generator sodium levels are expected to result in reduced steam generator corrosion. Although the potential cost savings cannot be accurately determined, the expense of reducing sodium often can be quantified (e.g. improved condensate polisher regeneration, etc.). In cases where the cost can be quantified but the benefit can be assessed only qualitatively, optimization consists of pursuing the minimum cost water chemistry program which provides the greatest expected benefit (e.g. lowest sodium levels). In other cases, both the costs and benefits can be quantified. For example, several alternate amines can be used for pH control in the secondary system. The costs associated with the amine program can be determined using EPRI chemWORKS™. The value of the benefits can be assumed as a first approximation to be proportional to the feedwater iron concentration achievable with a given amine program. The optimum amine program then would be the lowest cost program which achieved a target iron value. The target iron value would be determined on a more qualitative basis. For plants using condensate and/or blowdown demineralizers, the use of alternate amines could also increase sodium levels in the system, when demineralizers are

allowed to remain in service beyond the amine break. Optimization of the amine program must also at least qualitatively assess the cost of sodium in the system. This could be achieved by establishing an upper sodium limit in the system, and determining the minimum cost amine program which achieves both the sodium and iron targets.

The tradeoffs illustrated for the optimization of the pH control program are typical of many secondary water chemistry programs. Optimization for one component or portion of the system can lead to less than optimum conditions in other parts of the system. Therefore, an overall systems approach must be taken in developing the program. To do this effectively, a ranking system is provided in this section. The ranking system attempts to put the qualitative factors on a firmer basis. The system considers the merits of the secondary water chemistry initiatives presented in Section 3. Each utility must evaluate the merits of each initiative relative to plant specific design features, materials of construction, etc. Ultimately, a utility must decide where it sees its greatest risks and potential rewards.

It is suggested that procedures similar to those discussed in this section be applied as a basis for the plant specific secondary water chemistry program. The plan should be reviewed at a frequency of once every 2 years, to help assess whether strategic changes to plant chemistry or systems are required. The "Strategic Water Chemistry Plan" should be reviewed and approved by utility management. This approach will insure support from appropriate levels of management.

4.2 References

1. PWR Molar Ratio Control Application Guidelines, EPRI TR-104811, January 1995.
2. Titanium Dioxide Application Guidelines, TR-108002, Nov. 1997
3. Experience with Inhibitor Injection to Combat IGSCC in PWR Steam Generators, EPRI TR-105003, March 1995.
4. Nishikawa et al., "Experimental Investigation of Scale Formation at Heat Transfer Surface in PWR Secondary System," Chemistry in Water Reactors: Operating Experience and New Developments, pp. 579-586, SFEN, 1994.
5. W. Allmon, "Conditions for the Reduction of Sulfates," Workshop on Sulfur Species on the Degradation of Alloy 600 and Similar Alloys, EPRI NP-6710, March 1990.
6. J. Daret, et al., "Evidence for the Reduction of Sulfates Under Representative SG Secondary Side Conditions, and for the Role of Reduced Sulfates on Alloy 600 Tubing Degradation," presented at the Ninth International Symposium on Environmental Degradation in Nuclear Power Systems - Water Reactors, Newport Beach, California, August 1-5, 1999.
7. PWR Advanced Amine Application Guidelines, EPRI TR-102952, December 1994.

8. Boric Acid Application Guidelines for Intergranular Corrosion Inhibition (Rev. 1), EPRI NP-5558, Rev. 1, December 1990.

5

WATER CHEMISTRY GUIDELINES RECIRCULATING STEAM GENERATORS

5.1 Introduction

These guidelines reflect current understanding of the role of chemical transport, impurity concentrations, material selection, corrosion behavior, chemical analysis methods, and industry practices on the operation and integrity of steam generator systems.

The guidelines included in this section represent a condensation of the technical bases from Section 2, chemical control strategies from Section 3, and optimization issues from Section 4 into a generic program for recirculating steam generators (RSG). The current understanding suggests that it is the "consequence" of the contaminants (i.e., the chemical mix combined with the concentrating mechanisms in the steam generator) and the susceptibility of the alloys that establishes the corrosion concern.

It is recognized that steam generator designs vary significantly as do company management philosophies and economic conditions. Therefore, implementation of these guidelines requires "customization" to ensure they are specific to the needs of a given power station.

The existing Action Levels should be viewed as boundaries of the envelope within which plant specific optimization should be initiated, and within which plant-specific limits will often be located. However, it is recognized that, in some cases, plant-specific considerations will result in these boundaries being exceeded. This is acceptable, as long each deviation is appropriately documented and justified. The discussions in the previous sections and the flowcharts and tables of example values contained in Section 4 should be helpful in the effort to outline the appropriate limits for each plant.

This section includes control parameters at several sampling locations for most modes of operation. As previously indicated, the control parameter monitoring frequencies and action levels provided in the tables throughout this section must be included in the plant's water chemistry program to be compliant with NEI 97-06. Justifications for exceptions which are less restrictive or less conservative than any of these control parameters, control parameter monitoring frequencies or action levels, must be documented in the site Strategic Secondary Water Chemistry Plan or some other appropriate document. This requirement, in addition to the

development of the Plan itself, comprises the prescriptive portions of these guidelines that must be complied with to meet the "intent" of these guidelines with respect to NEI 97-06.

Typical corrective actions are recommended in several portions in this section. These corrective actions are not meant to be all-inclusive or universally applicable and should be modified for plant specific concerns.

This section presents specific guidelines for the addition of various combinations of chemical additives in units with a variety of secondary system materials and demineralization schemes. For some of these chemistry treatment and plant system combinations, extensive field experience and test data exist; for other combinations, this is not the case. The user of these guidelines should evaluate the information available regarding previous experience with these treatments to make an informed decision regarding the selection of any treatment program.

Some control parameters in this section call for the parameter involved to be monitored continuously. In the event that continuous monitoring is lost for any reason, the following actions are suggested: 1) the inoperable monitoring system be returned to an operable status as rapidly as practical, and 2) grab samples be taken and analyzed periodically until continuous monitoring is restored, as described in the Strategic Water Chemistry Plan or other plant documents.

5.2 Control And Diagnostic Parameters

The tables presented in this section include chemistry monitoring recommendations. Some of these are titled Control Parameters and some Diagnostic Parameters.

Control Parameters are those parameters that have a demonstrated relationship to steam generator degradation. Plant operations should support actions required to maintain these parameters within the specified values.

Diagnostic Parameters are important to monitor the program effectiveness, identify programmatic problems, or assist in problem diagnosis.

5.3 Action Levels

Three Action Levels have been defined for taking remedial action when monitored parameters are outside the recommended operating range. Deviations from chemistry concentrations normally achieved at a given station should be investigated. Action Levels prescribe values of a parameter above which long-term system reliability may be jeopardized. Operating below Action Level 1 values provides a greater degree of assurance that corrosive conditions will be minimized. Action Level 2 is instituted when conditions exist which are known to result in steam generator corrosion during extended full power (100%) operation. Action Level 3 is

implemented when conditions exist which will result in rapid steam generator corrosion and continued operation is not advisable.

The Action Levels and the associated chemistry limits are considered to be the first line of defense against secondary system and steam generator degradation. However, experience has shown that operation with impurity concentrations below Action Level limits has resulted in significant corrosion damage at several plants. Thus, more stringent chemistry controls, more sensitive monitoring techniques or more aggressive corrective measures may be warranted in some plants, based on plant-specific designs, operating histories or materials of construction. Impurity levels below which damage from all corrosion mechanisms is known to be negligible have not been clearly established. The philosophy of operation associated with these guidelines is that plants be operated with the lowest practicable impurity levels consistent with their circumstances. However, it should be recognized that certain actions taken to achieve low concentrations of impurities may cause a change in the ratio of highly soluble strong cation-to-anion impurities in the secondary plant. Concentration of a solution with a significant imbalance of either cations or anions in crevice regions will lead to development of caustic or acidic environments in crevices.

Action Level 1:

Objective: To promptly identify and correct the cause of an out-of-guideline value without power reduction.

Recommended Actions:

- a. Corrective actions should be implemented as soon as possible to return parameter to below Action Level 1.
- b. If parameter is not below the Action Level 1 value within one week following confirmation of excursion, go to Action Level 2 for those parameters having Action Level 2 values. The lack of progressive action criteria for many parameters is not intended to imply that remaining outside the normal range is satisfactory. In these cases, other chemical parameters, specifically associated with known corrosion conditions, are utilized for control.
- c. For those parameters not having an Action Level 2 value, an engineering justification should be performed for operating above Action Level 1 for an extended period of time.

Action Level 2:

Objective: To minimize corrosion by operating at reduced power while corrective actions are taken. Power reduction should be to a level which will reduce available steam generator superheat and heat flux in the crevices where concentration of aggressive chemicals can occur and provide sufficient system flow to maintain automatic operation while the source of the impurity is eliminated.

Recommended Actions:

- a. Take immediate actions to reduce power to a plant-specific level and achieve that power level within eight hours of exceeding Action Level 2 values, or as quickly as safe plant operation permits. The power level selected, typically ~30%, is governed by safe, automatic plant operational concerns and the need to reduce the heat flux (i.e., impurity concentration rate). Power de-escalation can be terminated if the source of impurity ingress is eliminated and parameter values are below Action Level 2. Escalation to full power can be resumed once Action Level 1 values are met.
- b. Return parameter to below Action Level 1 value within 100 hours of exceeding an Action Level 2 value (or entering Action Level 2 as a result of exceeding an Action Level 1 value for more than a week) or go to Action Level 3 for those parameters having Action Level 3 values.
- c. After an Action Level 2 excursion, excluding dissolved oxygen, consideration should be given to a hot soak or further reductions in power to promote removal of the specific contaminant from the steam generator.

Action Level 3:

Objective: To correct a condition which is expected to result in rapid steam generator corrosion during continued operation. Plant shutdown will minimize ingress and eliminate further concentration of harmful impurities. Plant shutdown also will reduce further damage to the steam generator by allowing cleanup of the impurities as a result of hideout return.

Recommended Actions:

- a. Shut down as quickly as safe plant operation permits and clean up by feed and bleed or drain and refill as appropriate until normal values are reached. Regardless of the duration of the excursion into Action Level 3, the plant should be taken to hot or cold shutdown. The judgment on maintaining the steam generator in a hot condition or progressing to cold shutdown should be based on the corrosion concern imposed by the specific impurity and the most rapid means to effect cleanup.

5.4 Corrective Actions

Typical corrective actions for various plant status modes are also presented. These corrective actions are not meant to be all-inclusive or universally applicable but should be considered. It should be noted that impurities may originate from within the system (weld repair, plant modification, or component replacement, etc.) or from without (condenser cooling water leak, makeup water contamination, etc.). Corrective actions vary accordingly.

When chemistry parameters exceed their normal concentrations, corrective actions should be implemented. The corrective actions which should be implemented are parameter and plant-specific. Each plant should have a predefined course of action which has been developed with attention to specific concerns. The following actions are considered typical:

- Identify and isolate sources of impurity ingress.
- Increase steam generator blowdown to maximum levels for removal of specific impurities.
- Increase sample and analysis frequencies for short-term trending and confirmatory analyses of critical chemistry parameters.

5.5 Plant Conditions

There are three plant conditions addressed in this section:

1. Cold Shutdown/Wet Layup - This condition encompasses periods when the RCS is $\leq 200^{\circ}\text{F}$; Modes 5 and 6 as defined by Standard Technical Specifications.
2. Heatup/Hot Shutdown ($>200^{\circ}\text{F}$, $\leq 5\%$ Power) - This condition covers periods when the RCS is $>200^{\circ}\text{F}$ but $\leq 5\%$ power; Modes 2, 3, and 4 as defined by the Standard Technical Specifications.
3. Power Operation - This condition applies to all periods when reactor power is $>5\%$; Mode 1 in the Standard Technical Specifications.

5.6 References

1. J. A. Armantano and V. P. Murphy. "Standby Protection of High Pressure Boilers " Proceedings of the 25th Annual Water Conference of the Engineers' Society of Western Pennsylvania, Pittsburgh, Penn., September 28-30, 1964, pp. 111-124.
2. Evaluation of Steam Generator Fluid Mixing During Layup, Research Project S164-1 Final Report Palo Alto, Calif.: Electric Power Research Institute, May 1983. NP-2993.
3. Plant Layup and Equipment Preservation Sourcebook, Research Project 2815-1 Interim Report, Palo Alto, Calif.: Electric Power Research Institute. March 1987. NP-5106.
4. G. Bohnsack, "Chemistry of Corrosion Inhibition and Surface Passivation of Mild Steel by Hydrazine in Power Plant Circuits," Corrosion 89, Paper 461, April 1989.
5. Laboratory Program to Examine Effects of Layup Conditions on Pitting of Alloy 600, Research Project S124-1 Final Report. Palo Alto, Calif.: Electric Power Research Institute, April 1983. NP-3012.
6. Neutralization of Steam Generator Denting, Volumes 1 and 2, Research Project S112-01 Final Report. Palo Alto, Calif. Electric Power Research Institute, September 1983. NP-3023.
7. S. L. Goodstine and J. J. Kurpen. "Corrosion and Corrosion Product Control in the Utility Boiler - Turbine Cycle." Combustion, May 1973.

8. F. Gabrielli and J. J. Kurpen. "Secondary Cycle Chemistry Control for a Pressurized-Water Reactor." Proceedings of the American Power Conference, Vol. 34, 1972.
9. Intergranular Attack of Alloy 600: High Temperature Electrochemical Tests, Research Project S193-1, Final Report. Palo Alto, Calif.: Electric Power Research Institute, May 1983. NP-3062.
10. Evaluation of Condensate Polishers, Research Project 623-3 Final Report. Palo Alto, Calif.: Electric Power Research Institute, June 1983. NP-3046.
11. S. W. Lurie and D. B. Scott. "The Effect of Sulfuric Acid on the Corrosion of Steam Generator Materials Under High Temperature Heat Transfer Conditions." Windsor, Conn.: Combustion Engineering, Inc., 1982. CE NPSD 188.
12. Causes of Denting, Volumes 4 and 5, Research Project S-157 Final Reports. Palo Alto, Calif.: Electric Power Research Institute, Dec. 1983. NP-3275.
13. Determination and Verification of Required Water Chemistry Limits: Model Boiler 5B Testing, Research Project SIII-1 Final Report. Palo Alto, Calif.: Electric Power Research Institute, July 1984. NP-3022.
14. Optimization of Metallurgical Variables to Improve Corrosion Resistance on Inconel Alloy 600, Research Project 1708-1 Final Report. Palo Alto, Calif.: Electric Power Research Institute, July 1983. NP-3051.
15. E. C. Potter and G. M. W. Mann. "The Fast Linear Growth of Magnetite on Mild Steel in High-Temperature Aqueous Condition." British Corrosion Journal, Vol. 1, 1965, p. 26.
16. Neutralization of Steam Generator Denting, Volume 2, Research Project S112-1 Final Reports. Palo Alto, Calif.: Electric Power Research Institute, Sept. 1983. NP-3023.
17. PWR Steam-Side Chemistry Follow Program, Research Project RP699-1 Final Report. Palo Alto, Calif.: Electric Power Research Institute, August 1982. NP-2541.
18. G. E. Von Nieda, G. Economy, and M. J. Wootten. "Denting in Nuclear Steam Generators--Laboratory Evaluation of Carbon Steel Corrosion Under Heat Transfer Conditions." Presented at the NACE Annual Meeting, March 1980.
19. G. Economy, W. M. Connor, and G. E. Von Nieda. "Laboratory Studies of the Effect of Chemistry on Denting in Nuclear Steam Generators." Presented at the NACE Annual Meeting, March 1982.
20. Rationale for Chemical Control of Feed and Boiler Water, Research Project RP1171-1 Final Report. Palo Alto, Calif.: Electric Power Research Institute, 1982. NP-3048.

21. Effect of Oxygen Concentration on Corrosion Product Transport at South Texas Project Unit 1, WO# 3388-17, Electric Power Research Institute, Palo Alto, Calif.: to be published May, 2000.
22. Steam Generator Performance Degradation, Electric Power Research Institute, Palo Alto, Calif.: September, 1991. NP-7524.
23. D. P. Siegwarth, "PWR Water Treatment Improvements: Cost-Benefit Analysis," Electric Power Research Institute, May 1988 (NP-5764).
24. N. L. Dickinson, D. N. Felgar and E. A. Pirsh, " An Experimental Investigation of Hydrazine-Oxygen Reaction Rates in Boiler Feedwater," Proceedings of the American Power Conference. p692-702, Vol. 19, 1957.
25. M. Bodmer and R. Svoboda. "The Chemistry of Feedwater for Boiling-Water and Pressurized-Water Reactors." Brown-Boveri Review, January 1976.

6

WATER CHEMISTRY GUIDELINES ONCE-THROUGH STEAM GENERATORS

6.1 Introduction

The guidelines presented in this section reflect the current understanding of the roles of chemical transport, impurity concentrations, and materials on the operation and integrity of once-through steam generator systems. They also reflect the technical bases of Section 2, the chemical control strategies of Section 3 and the optimization issues of Section 4.

The criteria for the establishment of the guideline parameters were:

- Impurity transport to the OTSG and main turbine should be limited to a practical and achievable minimum.
- Impurity concentration limits are maximum values consistent with currently known corrosion behavior of steam generator, turbine, and secondary system materials.
- Action Levels should be viewed as boundaries of the envelope within which plant specific optimization should occur.
- Action Level parameters can be readily quantified using currently available equipment and procedures.
- Guideline values are applicable to all cooling water sources.
- The guidelines allow site-specific adaptation to be consistent with design concerns and management objectives.

Using these criteria, guidelines have been formulated which provide chemistry control while retaining operating flexibility. These guidelines identify parameters to be measured and recommend actions for off-normal chemistry conditions. Wherever possible, literature sources are cited for justification.

This section includes control parameters at several sampling locations for most modes of operation. As previously indicated, the control parameter monitoring frequencies and action levels provided in the tables throughout this section must be included in the plant's water chemistry program to be compliant with NEI 97-06. Justifications for exceptions which are less restrictive or less conservative than any of these control parameters, control parameter

monitoring frequencies or action levels, must be documented in the site Strategic Secondary Water Chemistry Plan or some other appropriate document. This requirement, in addition to the development of the Plan itself, comprises the prescriptive portions of these guidelines that must be complied with to meet the "intent" of these guidelines with respect to NEI 97-06.

Typical corrective actions are recommended in several sections in this chapter. These corrective actions are not meant to be all-inclusive or universally applicable and should be modified for plant-specific concerns.

Because of the operating characteristics of the OTSG, secondary plant water chemistry requirements differ from those of a recirculating steam generator. This is particularly true during power operation (i.e., >15% reactor power) since there is no blowdown from an OTSG. In addition, since some impurities transported to the OTSG via the feedwater are transported almost quantitatively out of the OTSG by the superheated steam, the turbine rather than the steam generator may be the limiting corrosion concern. These guidelines assume the cycle and equipment design is appropriate for the OTSG system (i.e., full-flow condensate polishers, etc.).

Chemistry limits, responses to abnormal chemistry conditions, and the impact of such considerations on plant operation are discussed in this section. Four plant status modes are considered: Cooldown/Hot Soaks; Cold Shutdown/Wet Layup; Startup/Hot Standby and Reactor Critical at <15% Reactor Power; and Power Operation (>15% Reactor Power).

The chemistry limits and action levels are considered to be the minimum requirements for protection against steam generator, secondary system, and turbine corrosion. The guidelines are applicable for any cooling water source and are based upon the philosophy that plants should operate with the lowest practicable impurity levels consistent with their circumstances.

Some control parameters in this section call for the parameter involved to be monitored continuously. In the event that continuous monitoring is lost for any reason, the following actions are suggested: 1) the inoperable monitoring system be returned to an operable status as rapidly as practical, and 2) grab samples be taken and analyzed periodically until continuous monitoring is restored, as described in the Strategic Water Chemistry Plan or other plant documents.

6.2 Control And Diagnostic Parameters

The tables presented in this section include surveillance parameter recommendations. Some of these are titled Control Parameters and some Diagnostic Parameters.

Control Parameters are those parameters that have a demonstrated relationship to steam generator or turbine degradation. Plant operations should support actions required to maintain these parameters within the specified values. Control parameters are assigned Action Level values.

Diagnostic Parameters are employed to monitor program effectiveness and/or to identify programmatic problems. Diagnostic Parameters do not have assigned values/limits.

6.3 Action Responses

Three Action Levels have been defined for taking remedial action when monitored parameters are outside the recommended operating range. Deviations from chemistry concentrations normally achieved at a given station should be investigated. Action Levels prescribe values of a parameter above which long-term system reliability may be jeopardized. Operating below Action Level 1 values provides a greater degree of assurance that corrosive conditions will be minimized. Action Level 2 is instituted when conditions exist which are more likely to result in steam generator or balance of plant corrosion during extended full power operation. Action Level 3 is implemented when conditions exist which have the potential to result in rapid steam generator or balance of plant corrosion, and continued operation is not advisable.

The Action Levels and the associated chemistry limits are considered to be the first line of defense against secondary system and steam generator degradation. Since impurity levels over the design life of the plant below which corrosion damage is negligible have not been clearly established, more stringent chemistry controls, more sensitive monitoring techniques or more aggressive corrective measures may be advisable at some plants, based on plant-specific experience. The philosophy of operation associated with these guidelines is that plants be operated with the lowest practicable impurity levels consistent with their secondary system design. However, it should be recognized that certain actions taken to achieve low concentrations of the impurity may cause a change in the ratio of highly soluble strong cation-to-anion impurities. In such cases, tendencies for forming highly acidic or caustic solutions in crevices and on OTSG surfaces in upper regions of the bundle may increase. Of particular note in this regard is the possible development of IGA/SCC in the stress relieved Inconel 600 tubing.

Action Level 1:

Objective: To promptly identify and correct the cause of an out-of-guideline value without power reduction.

Recommended Actions:

- a. Corrective actions should be implemented as soon as possible to return the parameter to within Action Level 1.
- b. If a parameter has not been returned to below the Action Level 1 value within one week following confirmation of an excursion, an engineering evaluation should be performed to justify continuing to operate above Action Level 1.

Action Level 2:

Objective: To promptly identify and correct the cause of an out-of-guideline value prior to shutdown.

Recommended Actions:

- a. Corrective actions should be implemented as soon as possible to return the parameter to below Action Level 2.
- b. If the parameter is not below the Action Level 2 value within 100 hours following confirmation of the excursion, the plant should be in the hot standby condition within an additional 24 hours.
- c. An engineering evaluation should be performed to assess the cause of exceeding an Action Level 2 value, and corrective actions taken to minimize the occurrence of such excursions prior to returning to power operation.

Action Level 3:

Objective: To correct a condition which is expected to result in rapid corrosion during continued operation. Plant shutdown will minimize impurity ingress and limit exposure of steam generator, turbine and other secondary system materials to corrosive solutions. Plant shutdown will also reduce further damage to the steam generator by allowing cleanup of the impurities as a result of hideout return.

Recommended Actions:

- a. Shut down as quickly as safe plant operation permits (typically <6 hours) and clean up by feed and bleed or drain and refill as appropriate until normal values are reached. Regardless of the duration of the excursion into Action Level 3, the plant should be taken to hot or cold shutdown. Progressing to cold shutdown generally will be advisable to allow flushing of the upper regions of the OTSG.

6.4 Status Modes

These guidelines address steam generator status defined relative to the thermal and hydraulic conditions within the steam generator and the corresponding effects of the chemical environment. Specifically, there are four modes addressed in the guidelines:

1. Cooldown/Hot Soaks
2. Cold Shutdown/Wet Layup (RCS <200°F) - Modes 5 and 6 of Standard Technical Specifications
3. Startup, Hot Standby, and Reactor Critical at <15% Reactor Power (RCS >200°F, <15% Reactor Power) - Modes 1, 2, 3 and 4 of Standard Technical Specifications
4. Power Operation (>15% Reactor Power) - Mode 1 of Standard Technical Specifications

6.5 References

1. J.A. Armentano and V.P. Murphy, "Standby Protection of High Pressure Boilers," Proceedings of the 25th Annual Water Conference of the Engineers' Society of Western Pennsylvania, Pittsburgh, PA, pp. 111-124, September 28-30, 1964.
2. Methods for Evaluating Steam Generator Hideout Return Data: Case Study at North Anna, Research Project 2599-1. Palo Alto, CA, Electric Power Research Institute, December 1986 (NP-4940).
3. Plant Layup and Equipment Preservation Sourcebook, Research Project 2815-1, Interim Report, Palo Alto, CA, Electric Research Power Institute, March 1987 (NP-5106).
4. W.E. Berry, Corrosion in Nuclear Applications, J. Wiley & Son, New York, pp. 173-176, 1971.
5. Laboratory Program to Examine Effects of Layup Conditions on Pitting of Alloy 600, Research Project S124-1, Final Report. Palo Alto, CA, Electric Research Power Institute, April 1983 (NP-3012).
6. S.L. Goodstine and J.J. Kurpen, "Corrosion and Corrosion Product Control in the Utility Boiler - Turbine Cycle," Combustion, May 1973.
7. F. Gabrielli and J.J. Kurpen, "Secondary Cycle Chemistry Control for a Pressurized-Water Reactor," Proceedings of the American Power Conference, 34, (1972).
8. L.E. Johnson, "Effects of Fouling on Performance of a Nuclear Once-Through Steam Generator," Presented at the American Institute of Chemical Engineers (1972).
9. M.J. Bell and D.F. Levstek, "Nuclear Once-Through Steam Generator Tube Integrity," Southeastern Electric Exchange, Atlanta, GA, April 1977.
10. Rationale for Chemical Control of Feed and Boiler Water, Research Project RP11711-1 Final Report. Palo Alto, CA, Electric Research Power Institute, January 1984 (NP-3048).
11. Intergranular Attack of Alloy 600: High Temperature Electrochemical Tests, Research Project S193-1, Final Report. Palo Alto, CA, Electric Research Power Institute, May 1983 (NP-3062).
12. Evaluation of Condensate Polishers, Research Project 623-3, Final Report. Palo Alto, CA, Electric Research Power Institute, June 1983 (NP-3046).
13. S.W. Lurie and D.B. Scott, "The Effect of Sulfuric Acid on the Corrosion of Steam Generator Materials Under High Temperature Heat Transfer Conditions." Windsor, CT, Combustion Engineering, Inc., 1982 (CE NPSD 188).

14. Testing and Evaluation of a Moisture Separator Drain Demineralizer at Davis-Besse Nuclear Station, Palo Alto, CA, Electric Research Power Institute, April 1994 (TR-103833).
15. H.R. Copson and G. Economy, "Effect of Some Environmental Conditions on Stress Corrosion Behavior of Ni-Cr-Fe Alloys in Pressurized Water," Corrosion, **24**: (3), (1968).
16. H. R. Copson and W.E. Berry, "Qualification of Inconel for Nuclear Plant Applications," Corrosion, **16**: (2), (1960).
17. E. Howells, T.A. McNary, and D. E. White, "Boiler Model Test of Materials for Steam Generators in Pressurized Water Reactor Plants," Corrosion, **16**:(5), (1960).
18. M. Bodmer and R. Svoboda, "The Chemistry of Feedwater for Boiling-Water and Pressurized-Water Reactors," Brown-Boveri Review, January (1976).
19. O. Jonas, "Turbine Steam Purity," Corrosion, **34** (1978).
20. Effects of Alternate pH Control Additives in PWRs, Palo Alto, CA, Electric Power Research Institute, February 1988 (NP-5594).
21. F.G. Straub and H.A. Grabowski, "Silica Deposition in Steam Turbines," Transactions of the ASME, **67** (1945).
22. F.G. Straub, "Steam Turbine Blade Deposits," Bulletin Series No. 364, University of Illinois Engineering Experiment Station (1946).
23. F.W. Howell, "Turbine Blade Deposits," Power Engineering, **52** (1967).
24. M.J. Bell, N.J. Mravich, F.J. Pocock, & M.M. Rubright, "Solids Behavior in Once-Through Nuclear Steam Systems," Presented at the American Power Conference (1977).
25. M.A. Styrikovich, "Investigation of the Solubility of Low Volatility Substances in High Pressure Steam by Radioisotopes," International Conference of Radioisotopes in Research, **1** (1958).
26. J.H. Hicks, N. J. Mravich, F.J. Pocock, & M. J. Bell, "Water Chemistry for Nuclear Steam Supply Systems," Presented at the Liberty Bell Corrosion Course (1972).
27. R. V. MacBeth, "Fouling in Boiling Water Systems," Two-Phase Flow Heat Transfer, Harwell Series, UKAEA Research Group Reactor Development Division, A.E.R.E., Winfrith, England.
28. Kassen, W. R., "Electrochemical Potential Monitoring in the PWR Secondary Cycle of St. Lucie 2," Electric Power Research Institute, March 1995 (TR-104951).

29. Kassen, W. R., Seager, J. S., Beichel, K. E., and Millett, P. J., "On-Line Electrochemical Potential Monitoring in the Feedwater at the St. Lucie 2 PWR," Proc. of Intl. Conf., Chemistry in Water Reactors: Operating Experience and New Developments, SFEN, Nice, France, pp. 638-641, April 1994 (Volume 2).
30. Litman, R., "Experience at Seabrook Nuclear Station," presented at Newport Beach EPRI Water Chemistry Meeting, November 1998.

7

DATA: COLLECTION, EVALUATION, AND MANAGEMENT

7.1 Introduction

The primary purposes of secondary cycle chemistry controls are to minimize general corrosion and prevent localized corrosion of plant materials with the expectation of attaining the design life of all components. With existing water chemistry guidelines the limiting condition for attaining this goal is any process which results in concentration factors in excess of approximately 10^6 . Crevice areas and dryout regions in steam generators and wet-dry transition zones in turbines provide such concentration factors. Corroding surfaces which do not maintain a protective oxide layer may not provide service for the design life, and corrosion products generated from corrosion processes in the balance of plant are transported to the steam generator where deposition may result in localized corrosion of steam generator surfaces and fouling of tubes. The combined effects of stress, temperature, chemical environment, and metallurgy determine whether a specific mode of corrosion occurs. Once a particular component is installed in an operating plant system only the chemistry environment can be modified to impact the corrosion process, although temperature reduction is also an option with thermal penalties.

The effectiveness of the secondary cycle chemistry control program must be continually evaluated to determine if chemistry conditions in the bulk water are minimizing or preventing local corrosion processes. During operation, corrosion processes can only be inferred by analyzing treatment additives, impurities, and corrosion products in conditioned samples withdrawn from bulk process streams. Non-representative samples and matrix effects will provide false information, and a program is necessary to address QA/QC and sampling issues. Recent developments in modeling have enabled local conditions to be evaluated while minimizing sampling and analytical requirements. The **EPRI chemWORKS™** software is a valuable tool for assessing local chemistry conditions.

In Sections 5 and 6, secondary water chemistry guidelines are established for units with recirculating steam generators and once-through steam generators. Recommendations are made for specific actions based on continuous monitoring and laboratory analysis results. Tables 7-1 and 7-2 are summaries of the continuous instrumentation recommendations for units with recirculating steam generators and units with once-through steam generators, respectively, at power operation. In these tables a distinction is made between the instrumentation array

Table 7-1
Continuous Instrumentation Suggestions for Recirculating Steam Generators

<u>Analysis</u>	<u>Blowdown</u>	<u>Feedwater</u>	<u>Condensate Demineralizer Outlet</u>	<u>Condensate Pump Discharge</u>	<u>Individual Hotwells</u>
Specific Conductivity	D	D	D	D	---
Cation Conductivity	C	D	D	D	D
pH	D	D	---	D	---
Dissolved Oxygen	---	C	---	C or D*	---
Sodium	C	D	D	D	D
Hydrazine	---	C	---	---	---

C Recommended control parameters of Section 5.

D Suggested for rapid problem diagnosis.

* D only if plant has representative FW sampling system and no copper alloy FW heaters

Table 7-2
Continuous Instrumentation Suggestions For Once-Through Steam Generators

<u>Analysis</u>	<u>Feedwater</u>	<u>Moisture Separator Drains</u>	<u>Cond. Demin. Outlet</u>	<u>Cond. Pump Discharge</u>	<u>Individual Hotwells</u>	<u>Blowdown ($<15\%$ Power)</u>
Specific Conductivity	D	D	D	D	---	---
Cation Conductivity	D	D	D	D	D	C
pH	D	---	---	---	---	---
Dissolved Oxygen	C	---	D	C or D*	---	---
Sodium	C	D	D	D	D	C
Hydrazine	C	---	---	---	---	---

C Recommended control parameters of Section 6.

D Suggested for rapid problem diagnosis.

* D only if plant has representative FW sampling system and no copper alloy FW heaters

consistent with the chemistry control parameters of Sections 5 and 6 and the optional instrumentation array recommended for problem diagnosis.

In addition to EPRI chemWORKS™, there are other tools available to assess local chemistry conditions and performance of systems important to the overall chemistry control. During shutdown, a hideout return study may provide an indication of concentration processes while the system was operating, and subsequent inspections may indicate the extent and mode of corrosion while the plant was operating. The chemistry environment may require modifications depending on the result of operational chemistry, hideout return, and inspection evaluations. Mass balance relationships can be used to evaluate impurity input sources. In turn, by understanding these inputs, corrective measures can be taken to reduce impurity inventories and/or concentrations. The mass balance tool can be used for ionic species as well as corrosion products. Lastly, for plants that utilized condensate polishers and/or blowdown demineralizers, resin analyses can provide an indication of the performance of the resins and their impact to the chemical control of the secondary cycle.

7.2 QA/QC Considerations

7.2.1 Basis for Generating Chemistry Data of Known Quality

ASTM and other sources have developed specific standards and guidelines for QA/QC practices that are applicable to power plant chemistry programs. The QA/QC program given in INPO 88-021 (1) Guidelines is sufficient for chemistry control and will not be repeated here. However, selected aspects of the QA/QC program are discussed below since they have a direct impact on secondary chemistry control.

7.2.2 Data Management

The *PWR Secondary Water Chemistry Guidelines* do not give explicit requirements for a chemistry data management system, but offer desirable features which can be incorporated into a plant-specific system when resources become available. A main feature of a data management system should be retrievability of results in a timely manner. Ideally, the data management system should preferably provide for automated input from chemical process instrumentation and manual input from grab sample analyses. A well designed chemistry data management system should provide the following to enable reviews to identify actual and potential problems as soon as data are generated or recorded:

- system being sampled and sample point
- plant status and operating mode (e.g., power level, blowdown flow rate, polisher configuration, etc.)
- chemistry limits and analysis frequency
- analysis time

- results of current and previous samples
- actions taken if limits not met (e.g., chemical additions, changes in blowdown flow rate or demineralizer/polisher status, etc.)

Conceptually a state-of-the-art chemistry data management system would be capable of interfacing with **EPRI chemWORKS™** (see Section 7.5.2), linking plant data files to the PWR Secondary Chemistry Simulator (PWRSCS) to perform automated evaluations. Other desirable features of the data management system include:

- plot various analysis and plant parameters as a function of time, with real time plots available from process instrumentation
- perform mass balances to determine the fate of various species in process streams
- plot QC results on control charts and evaluate the results for conformance requirements (a separate data management system can be used to perform this function)

7.2.3 QC Considerations for Secondary Chemistry Control

An important aspect of the QC program is the analysis of QC samples to verify analytical performance. Analysis of QC samples should reflect the matrix of the samples under analysis unless the matrix is known not to impact the analysis result (i.e., the analysis of a QC sample in demineralized water does not necessarily verify sulfate in a steam generator blowdown sample under layup conditions with 500 ppm hydrazine and 50 ppm ammonia if the hydrazine and ammonia interfere with the analysis and pretreatment to remove the hydrazine and ammonia introduces contamination). The following are examples of matrix conditions which could impact analysis results:

- QC samples should be prepared in the appropriate matrix unless the matrix effect has been shown to be negligible.
- To the degree practicable, QC samples should be pretreated in the identical manner as samples under analysis (e.g., if samples are passed through ion exchange resin to remove chemicals the QC samples should be treated in the identical manner to reflect potential contamination).
- Samples analyzed for hideout return studies may require special considerations since high levels of impurities such as silica and sulfate can affect analysis results (2).

A relatively simple approach to difficult matrix effects is to spike samples to increase the parameter of interest by approximately a factor of two and determine the percent recovery.

The chemistry process instrumentation should be calibrated and maintained to the degree necessary to provide accurate, real-time data. Additional guidance is provided in ASTM D-3864 (3).

Chemicals used as treatment additives can be a source of impurities to the secondary cycle. For example, purchasing specifications should ensure that sodium, chloride, and sulfate are limited in

treatment additives. Impurities such as ethylene glycol should be limited in ETA or as appropriate in other amines.

7.3 Sampling Considerations

Efforts should be made to assure that a sample is representative of the process stream or vessel of interest. Chemistry results are no better than the validity of samples under analysis. Long sample lines and improper sample conditioning can lead to results which have little to do with the process stream being analyzed. Non-representative samples can result from:

- chemical reactions during transit in the sample line (e.g., hydrazine and oxygen)
- chromatographic effects of trace impurities as a result of adsorption on oxides
- plateout of particulates
- delays in sample transport affecting sample times

A major consideration in some steam generator designs is the effect of sample location in the steam generator. Some steam generators have provisions for sampling the downcomer region and the blowdown, and impurity concentrations may be different at these locations, depending on specific steam generator design. High blowdown flow rates reduce impurity levels, but in some designs higher blowdown flow rates direct more feedwater toward the blowdown lane, and the lower impurities are a result of analyzing samples enriched with feedwater rather than the water in contact with the steam generator tubes.

Existing sampling systems often do not take into account design features presently considered appropriate. Plants upgrading their sampling systems should consider improved sampling practices such as those given by ASTM and ASME (4 - 7).

Generally, sample lines should be as short as feasible and of the smallest practicable bore to facilitate flushing, minimize conditioning requirements, and reduce lag time and changes in sample composition, and provide adequate velocity/turbulence. The current recommendation is to withdraw all samples at about 6 feet/sec or more (i.e., to achieve turbulent flow) to minimize deposition of particulates and sorption of dissolved species within tube wall deposits.

Maintaining the selected velocity is necessary to obtain a representative sample of particulates. Other sampling considerations are as follows:

- Local samples are preferable for dissolved oxygen rather than remotely analyzed samples since reactions can occur in long sample lines. This is particularly important for feedwater samples due to hydrazine reactions in the sample line.
- The sample line material should be compatible with the constituent under analysis (e.g., long runs of plastic or carbon steel tubing are inappropriate).
- Sample splitting is often used to obtain multiple streams from a single source or to provide bypass flow to an analyzer. Changing the flow rate of one stream can change the flow

characteristics of the other streams in split samples and can alter the accuracy of the analysis. A particular concern is extracting split samples for corrosion product monitoring.

- Sample taps should be located at least 25 pipe diameters downstream of chemical injection points.
- Liquid samples should be extracted from the side of horizontal pipes or from vertical pipes. Single-port taps are adequate if sufficient velocity is maintained to avoid deposition, whereas multi-port nozzles can be provided to extend across a pipe diameter to obtain an average sample of a cross section.
- Continuously flowing samples are preferred. ASTM D 3370-95 recommends the following to ensure representative samples from streams not continuously flowing. Grab samples should be withdrawn for analysis after flushing for a minimum of three sample line volumes at a sample flow rate of about 6 feet/sec or more. Stagnant tanks should be recirculated for a volume equivalent to three tank volumes prior to withdrawing a sample. These recommendations may not always be practicable, but should be followed to the degree possible.
- Special considerations should be given to sampling the blowdown of recirculating steam generators where the feedwater is injected in a manner that directs the incoming feedwater to the path of the blowdown extraction piping. The samples withdrawn will be enriched with feedwater at high blowdown rates.

A major concern is sampling the steam generator during blowdown isolation or shutdown conditions. Valid hideout return studies are contingent on obtaining a representative sample. If the plant is at temperature during blowdown isolation, blowdown samples may not be representative as a result of excessive sample transport times. Sample collection time should reflect sample transport time in the sample line if delays are significant. During shutdown periods, with or without blowdown isolation, pressure may not be available to provide sufficient head for sample flow; local samples must be withdrawn for analysis. This is a particular concern during layup conditions. If a recirculation pump is not used, local samples must be collected, and purging requirements may not be defined. Replicate samples should be collected at the highest practicable purge rate to establish sample validity. A particular concern is sampling after a chemical addition during layup without recirculation. In this case, local samples will be non-representative unless nitrogen sparging through the blowdown line is used. Each plant should evaluate the above for relevance.

7.4 Effectiveness Assessments

Integration of ISI and NDE data into the chemistry program provides a feedback loop between station chemistry and materials performance which should focus on reducing corrosion and extending component life. Examples of areas for consideration are:

- sludge burden in the steam generators relative to feedwater metals transport and the chemical treatment program
- deposits affecting steam generator water level in OTSGs relative to operational chemistry
- pipe thinning as a result of FAC relative to the high temperature pH associated with the chemical treatment program and condensate dissolved oxygen levels
- thermal performance of the secondary systems
- steam generator tube fouling and steam pressure loss relative to the chemical treatment program
- orifice fouling and operational chemistry
- NDE inspection results of steam generator tubes during outages relative to
 - operational chemistry
 - cooling water ingress
 - condensate polisher and blowdown demineralizer operation and regeneration practices
 - impurities in treatment additives
 - air inleakage
 - hideout return data
- turbine corrosion issues and deposits relative to operational chemistry, particularly for OTSGs

An example of an assessment is relating steam generator tube corrosion modes and rates from NDE results with

- operational chemistry (e.g., molar ratio control practices, high hydrazine usage, boric acid chemistry, impurity ingress and the sources, etc.)
- hideout return evaluations
- hot soak and crevice flushing practices
- sludge inventory and feedwater metals transport
- sludge lancing and sludge analyses
- tube examinations, including deposit analyses
- startup and layup practices (e.g., use of oxygenated auxiliary feedwater, flushing/cleanup paths, etc.)

The assessment program is important is evaluating the need and potential effectiveness for chemical cleaning of the steam generators and remedial actions to mitigate IGA/SCC.

7.5 References

1. Guidelines for Chemistry at Nuclear Power Stations, INPO 88-021.
2. S. Harvey, "Recent Advances in the Simultaneous Determination of Anions and Silica in High Purity Water," Journal of Chromatography, Vol. 546, June 1991.
3. ASTM Specification D-3864, "Standard Guide for Continual On-Line Monitoring Systems for Water Analysis."
4. ASTM D 5540-94a, "Standard Practice for Flow Control and Temperature Control for On-Line Water Sampling and Analysis."
5. ASTM D 3370-95a, "Standard Practices for Sampling Water from Closed Conduits."
6. ASTM D 1192-95, "Standard Specification for Equipment for Sampling Water and Steam in Closed Conduits."
7. ASME PTC 19.11 - 1997, "Steam and Water Sampling, Conditioning and Analyses in the Power Cycle."
8. S. B. Dalgaard and M. O. Sanford, "Review of Hydrazine/Oxygen Kinetics," Materials Performance, v21, n4, p32-38, April 1982.
9. PWR Molar Ratio Control Application Guidelines, Volume 3: Hideout Return Evaluation Guidelines, EPRI TR-104811-V3, November 1995.
10. Advanced Amine Application Guidelines, Revision 1, EPRI TR-102952-R1, December 1994.
11. Evaluation of Steam Generator Chemical Hideout at the Prairie Island PWR, EPRI NP-55592, February 1988.
12. Application of Crev-Sim to Steam Generator Crevice Impurity Inventory Prediction, Research Project S416, April 1997.
13. Prairie Island-2 Steam Generator Hideout, EPRI NP-7236, April 1991.
14. Steam Generator Crevice Chemistry Phase 5, Combustion Engineering Report CE-NPSD-1101-P, February 1998.
15. Characterization of PWR Steam Generator Deposits, EPRI TR-106048, February 1996.
16. PWR Advanced All-Volatile Treatment, EPRI TR-100755, July 1992.

17. Qualification Testing of Three Amines in an OTSG Plant, EPRI 103098, March 1994.
18. Qualification of 5-Aminopentanol for PWRs, EPRI TR-107948, April 1997.
19. Advanced Amine Application Guidelines, EPRI TR-102952-R2, October 1997.

A

INTEGRATED EXPOSURE EVALUATIONS

1.0 Introduction

A new diagnostic parameter, integrated exposure, is being included in this revision of the *PWR Secondary Water Chemistry Guidelines*. The integrated exposure term is not a new idea to the *Guidelines*, nor is it a fundamental change to the way utilities view the potential harm impurities will cause to steam generators. Compared to the concentration limits for impurities in previous versions of the *Guidelines*, integrated exposure limits will allow a better estimation of the amount of impurities which accumulate in crevices, and therefore, also a better estimation of the relative potential harm to SGs. There is currently no correlation of integrated exposure to corrosion rates; however, since it is widely agreed that for any pH or crevice chemistry, smaller amounts of impurities are better, integrated exposure can be utilized on a relative scale.

It is suggested that plant personnel begin calculation of IE during startup as soon as the plant begins to increase power assuming a linear hideout rate with power. Calculation of IE beginning at 0% power will bound the amount of IE at low power operation and possibly provide more insight into when impurity concentrations in the crevice cause the most risk.

The simplest method of calculating integrated exposure is to integrate the impurity concentration over the number of days the crevice is exposed (continuous cycle length). This integration is just the area under the curve of a plot of the time during the cycle vs. the product of concentration of impurity and power, and is easily calculated with the use of a computer spreadsheet.

7.0 References

1. A. P. L. Turner, Time Dependant Model for Crevice Fouling, Corrosion, and Tube Degradation, draft report, EPRI Project S407-31, February 1990.

